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Lifetime Prediction for Supercapacitor-powered Wireless Sensor Nodes

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***Abstract*—Energy-aware task scheduling is a novel research direction for wireless sensor networks. It depends on accurate models for lifetime prediction. In other terms, nodes must be aware of present and future energy resources. This paper addresses the first step towards reaching this goal: It explores discharging-characteristics of supercapacitors, discusses analytical discharging-models for lifetime prediction, and evaluates these models by comparing them with real discharging curves.**

I. Motivation

In the recent past, energy-efficiency has become a major research topic in the field of wireless sensor networks. Though it can prolong a sensor node's lifetime, energy depletion will eventually emerge long before the desired date. Since battery capacities are not expected to rise in orders of magnitude within the near future, provided that larger-sized batteries are not an option, and since replacement of batteries is usually infeasible, a different card must be drawn.

Within the last couple of years, the potential of harvesting energy from the environment has become more and more attractive. Various harvesting solutions are possible, among the sources being light, radio frequency, wind, vibration, or temperature difference. Here, sunlight is highly promising, since it produces a sufficient amount of energy to supply wireless sensor nodes, which draw currents between several μA in the sleep state and some mA in full-operation mode.

Yet, sunlight—but also other sources—have the drawback of not harvesting energy continuously. Furthermore, the amount of energy produced may vary significantly depending on the environmental conditions. This leads to the necessity to buffer energy, so that nodes do neither suffer from temporal energy depletion nor is their operation restricted to periods of incoming energy.

Despite the rich bouquet of energy buffers available, most of them reveal a considerable shortcoming: the amount of energy stored cannot be estimated easily. However, this ability is advantageous or even mandatory, as it allows for adaptive duty-cycling or may shrink the chance of accidental energy depletion caused by running a highly energy-consuming task during periods of low energy reserves. Energy-awareness may also allow for performing these tasks during periods of energy excess. Thus, energy-aware task scheduling becomes possible.

In the recent years electric double-layer capacitors with high capacities have become available. They fill the gap between capacitors and rechargeable batteries and can store enough energy to keep up-to-date sensor nodes alive for a couple of days. Their main advantage over rechargeable batteries is the high number of possible charge-discharge cycles. While a lifetime of 2-3 years can be expected for lithium-ion polymers, supercapacitors can last for 10 years or even more. Supercapacitors do not need a complex charging circuit and render easy estimation of their energy reserves possible.

Examples of supercapacitors are Panasonic GoldCaps [1] and SAMWHA GreenCaps [2], which we have used in a solar energy-harvesting power-supply. In this paper, we will present our first experiences on this matter. We will develop and assess models for energy estimation, enabling node lifetime prediction. These models build up the cornerstone of a more complex system that will be developed in future research. This system is compassed to enrich our model with a prediction of future incoming energy, e.g., obtained from a solar cell.

II. Related work

Several approaches for self-sustaining power supplies for wireless sensor nodes exist. The Enviromote [3] is using a solar cell as power source and NiMH batteries for energy storage. Among the design goals are easy circuit design and cheap energy storage devices. The authors present charging and discharging characteristics of their power supply.

A solar harvesting supply with lead acid batteries for the IRIS [4] platform is developed in [5]. It targets at large capacity energy storage and keeps the solar cell at a static maximum power point.

Prometheus [6], also employing a solar cell, is based on a two-stage energy storage system. A supercapacitor serves as the primary energy source, which supplies the sensor node and limits access to the secondary source, a rechargeable Li^+ battery, to prolong the lifetime of the latter. Charging and discharging behavior of the circuit and supercapacitors are examined. A striking observation is that—for the presented power supply—a 22 F supercapacitor outperforms its 10 F and 50 F counterparts. The authors also take a first step into the direction of energy-aware scheduling by adapting the duty cycle to the current supercapacitor voltage. Prometheus has been successfully deployed in the Trio testbed [7].

Another approach is found in [8]. The Everlast platform stores energy obtained from a solar cell in a supercapacitor solely. In order to increase the efficiency of the solar cell, i.e., to maximize the amount of energy available, maximum power point tracking (MPPT) is performed. The authors claim that their platform can operate for as long as 20 years while preserving high data rates.

III. Energy Harvesting Platform

As a first step on our road to energy-aware task scheduling on wireless sensor nodes, we have developed a prototype of a solar energy-harvesting platform as depicted in Fig. 1. It supplies an IRIS sensor node from Crossbow Technology. This prototype uses a solar cell as its energy source. The solar cell is currently feeding a supercapacitor via a simple circuit consisting of a Schottky-Diode to avoid discharge during cloudy periods or at night and a Zener-Diode to prevent over-charging of the supercapacitor. Here, the charging maximum is limited to approximately 2.3 V, which is the specific maximum voltage allowed for GoldCaps.

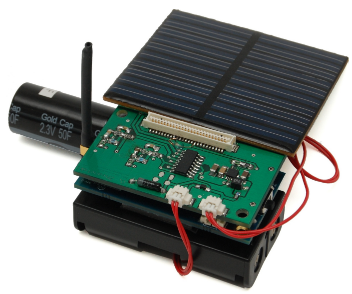


Fig. 1: Energy Harvesting Platform for the IRIS node

The discharging circuit consists of the DC-DC buck-boost converter TPS61221 from Texas Instruments [9], which ensures a stable and constant supply voltage of 3.3 V. The converter starts converting at an input voltage of 0.7 V and has an efficiency of up to 95%. This converter has been selected because of its low quiescent current of 5.5 μA and its high efficiency even at low currents. Figure 2 depicts the efficiency for different output currents and input voltages. The input voltage is equal to the supercapacitor voltage, which will range from 0.7 V to 2.3 V. For node-operation in normal mode with a current of a few mA the efficiency of the converter will be higher than 80%. Even in sleep mode with a current of a few μA, the efficiency will remain well above 60%. Most other DC-DC-converters, built for high efficiency at larger currents, can achieve an efficiency of 10% for low currents only.

IV. Lifetime Prediction

In this section, models for predicting supercapacitor voltage V_C and thus estimating node lifetime will be derived.

A. Simple Model

As a first step we analyze the temporal behavior of the supercapacitor voltage V_C in a simple model, i.e., we neglect self-discharge. Figure 3 illustrates the simplified circuit, which only consists of the supercapacitor with capacitance C, the DC-DC-converter, and the sensor node.

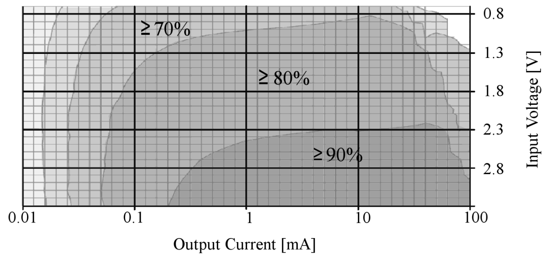


Fig. 2: Efficiency of the Texas Instruments DC-DC-converter TPS61221 [9]

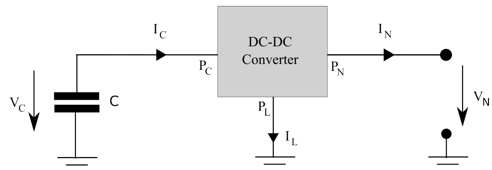


Fig. 3: Simplified Discharge Circuit

Due to conversion losses and the current I_L consumed by the DC-DC-converter, the input power P_C is larger than the output power P_N:

$$P_N = P_C - P_L = \eta \cdot P_C = \eta \cdot V_C \cdot I_C, \tag{1}$$

where η is the efficiency of the converter. Note that we assume a constant power state of the node, i.e., the current I_N consumed by the node is constant. In addition, the voltage V_N provided by the DC-DC-converter is stable and constant, so that $P_N = V_N \cdot I_N = \text{const.}$

Supercapacitors behave like normal capacitors with

$$I_C = -C \cdot \dot{V}_C, \tag{2}$$

so that we can combine (1) and (2) to

$$P_N = -\eta \cdot V_C \cdot C \cdot \dot{V}_C. \tag{3}$$

For simplicity, we assume η to be constant, so that the differential equation (3) can be solved as follows

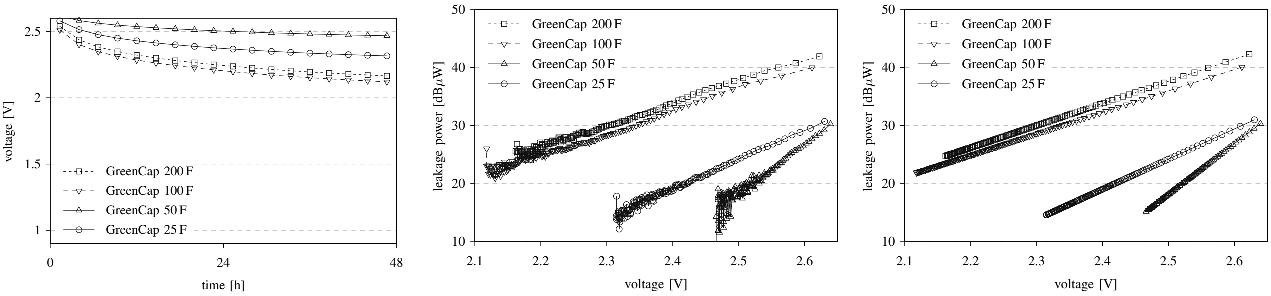
$$\int_{t_0}^{t_0+T_{life}} \mathrm{d}t = -\frac{\eta C}{P_N} \int_{V_{C,0}}^{V_{min}} V_C \mathrm{d}V_C \tag{4}$$

Here, the current time is denoted t_0, and $V_{C,0}$ is the voltage of the supercapacitor at this time. The minimum voltage V_{min} is required by the DC-DC-converter for proper and reliable function. The elapsed time until V_C has dropped to V_{min} is T_{life}; the latter will be referred as the expected lifetime at time t_0. Finally, solving (4) yields

$$T_{life} = \frac{\eta C}{2 P_N} \left(V_{C,0}^2 - V_{min}^2 \right). \tag{5}$$

B. Leakage Current

The previously developed model must be extended, if the current I_C drawn from the supercapacitor drops to a value close to the leakage current I_{leak} of the supercapacitor. We expect that this will be the case for low duty cycles of the



(a) GreenCaps, Self-Discharge (b) GreenCaps, Leakage Power (c) GreenCaps, Leakage Power Estimation

Fig. 4: Supercapacitor self-discharge behavior of GoldCaps and GreenCaps

attached sensor node—e.g., the IRIS platform draws a current $I_{\text{N}} \approx 20\,\mu\text{A}$ in the sleeping-mode [5].

We have recorded self-discharge time-voltage curves of different supercapacitors. Figure 4a shows the supercapacitor voltage of GreenCaps with capacities between 25 and 200 F. All capacitors have been charged close to the maximum allowed voltage of 2.65 V. It is remarkable that self-discharge is highly correlated with the voltage. This behavior matches the one for a different model shown in [1] and our additional recordings for GoldCaps (that are left out for brevity).

From these recordings, the leakage power of the supercapacitors can be approximated numerically from

$$E(V_{\text{C}}) = \frac{CV_{\text{C}}^2}{2} \;\Rightarrow\; P_{\text{leak}}(V_{\text{C}}) \approx \frac{\Delta E(V_{\text{C}})}{\Delta t} = \frac{C \Delta V_{\text{C}}^2}{2\Delta t}, \quad (6)$$

where ΔV_{C}^2 is the difference of V_{C}^2 at time t and V_{C}^2 at time $t + \Delta t$. The corresponding results are shown in Fig. 4b. The noise in the lower voltage regions is due to the noisy measurement of the slowly decreasing voltage. Note that power is shown in logarithmic scale, giving rise to an exponential behavior of leakage power:

$$P_{\text{leak}} \approx P_0 \cdot \exp(\alpha V_{\text{C}}). \quad (7)$$

We have determined estimations according to (7) for all of the tested supercapacitors using least squares. The results are displayed in Fig. 4c. The estimations follow the numerical approximation of P_{leak} closely.

C. Refined Model

Taking leakage power into consideration, (1) becomes

$$P_{\text{C}} - P_{\text{leak}} = P_{\text{N}} + P_{\text{L}}, \quad (8)$$

and therefore (3) has to be rewritten using (7) as

$$P_{\text{N}} = -\eta \cdot V_{\text{C}} \cdot C \cdot \dot{V}_{\text{C}} - P_0 \cdot \exp(\alpha V_{\text{C}}). \quad (9)$$

The solution to this equation can be found using mathematical software, such as Maple:

$$T_{\text{life}} = -\frac{\eta C}{2P_{\text{N}}} \left[V_{\text{C}}^2 - \frac{2V_{\text{C}}}{\alpha} \ln\left(1 + \frac{P_0 \exp(\alpha V_{\text{C}})}{P_{\text{N}}}\right) - \frac{2}{\alpha^2} \sum_{n=1}^{\infty} \left(-\frac{P_0 \exp(\alpha V_{\text{C}})}{P_{\text{N}}}\right)^n \frac{1}{n^2} \right]_{V_{\text{C},0}}^{V_{\min}} \quad (10)$$

Unfortunately, this equation is highly complex due to the ln, exp, and the dilog (the infinite sum). It is thus not suitable to be evaluated on sensor nodes. However, it is a good first step in order to gain insight into realistic discharging behavior of nodes running on supercapacitors. Simplification of the equation will be future work.

V. Model Evaluation

In this section the models developed in Sect. IV are checked against discharging curves recorded for duty cycles ϑ of 1, 10, and 100% on the IRIS platform. Figures 5a to 5c show the remaining supercapacitor lifetime, i.e., the time elapsed until V_{C} falls below $V_{\min} = 0.9\,\text{V}$. Smaller values of $V_{\min}$, as proposed in Sect. III, lead to a too low output voltage V_{N}.

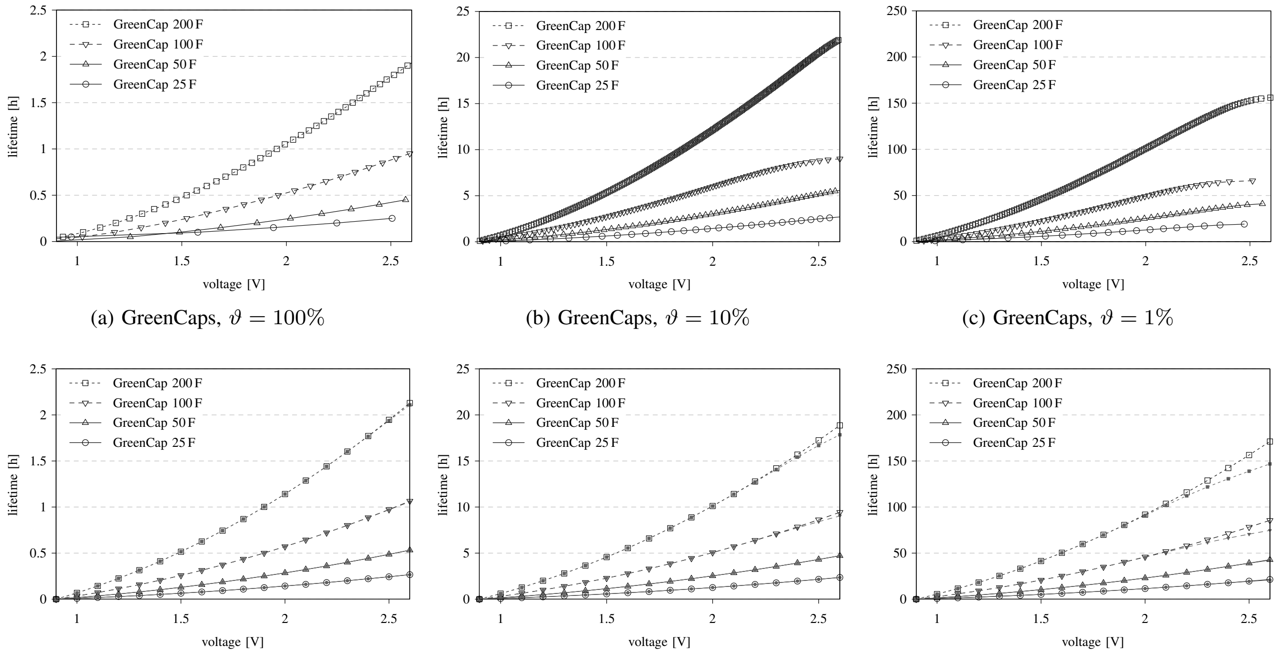
The results show that—as expected in Sect. IV-B—self-discharge has an impact on remaining lifetime for low duty cycles, while it can be neglected for high ones. This is indicated by the dip for large values of V_{C} in case of $\vartheta = 1\%$ in Fig. 5c as opposed to the behavior for $\vartheta = 100\%$ in Fig. 5a. As a result, lifetime would be dramatically overestimated for low duty cycles, if the simplified model were used.

Knowing about the real discharging behavior, we have computed lifetime predictions using (5) and (10). Having a constant node supply voltage of $V_{\text{N}} = 3.3\,\text{V}$, we used $I_{\text{N,act}} = 20\,\text{mA}$ for the active and $I_{\text{N,sleep}} = 20\,\mu\text{A}$ for the sleeping mode and averaged P_{N} according to the duty cycle ϑ :

$$P_{\text{N}} = V_{\text{N}} \left(\vartheta \cdot I_{\text{N,act}} + (1 - \vartheta) \cdot I_{\text{N,sleep}}\right)$$

Based on Fig. 2 we assume an efficiency $\eta_{\text{act}} = 85\%$ for the active and $\eta_{\text{sleep}} = 75\%$ for the sleeping mode and averaged η as we did with P_{N}.

The prediction results are displayed in Fig. 5d through 5f. The curves with the open markers have been computed using the simplified model, whereas their filled counterparts come from the refined one. The results reveal that the models give accurate predictions for a large duty cycle and for low values of V_{C} in case of a low duty cycle. For $\vartheta = 1\%$ the two models show significant differences for a large V_{C}. During evaluation, we experienced that the dilog term in the refined model has only a marginal influence on prediction accuracy and can thus be omitted. The combined ln-exp term, however,



(a) GreenCaps, $\vartheta = 100\%$ (b) GreenCaps, $\vartheta = 10\%$ (c) GreenCaps, $\vartheta = 1\%$

(d) GreenCaps, $\vartheta = 100\%$ (e) GreenCaps, $\vartheta = 10\%$ (f) GreenCaps, $\vartheta = 1\%$

Fig. 5: Measured vs. predicted node lifetime for GreenCaps for duty cycles $\vartheta = 1\%$, 10%, 100%

should not be dropped, as it gives better prediction of T_{life} if the supercapacitors are almost fully charged.

Although we have solely calculated averages for P_{N} and η and taken rough estimates for the values in the two node states (sleeping and active), the curves follow the realistic ones considerably well and are thus promising. Yet, fine-tuning of the parameters may be required, as soon as the models are simplified, as this step already introduces prediction errors. In contrast, it appears that a more detailed modeling of the power-states and the DC-DC efficiency may not be required.

VI. Conclusion and Next Steps

In this paper, we have presented models for predicting the lifetime of wireless sensor nodes using a supercapacitor-based power supply. These models have been evaluated using real discharging behavior of this power supply and found to match the real discharging behavior closely.

The estimation and prediction models derived in this paper serve as a first groundwork. However, the influence of temperature or supercapacitor age has not been taken into consideration thus far. Hence, our models must be refined. In contrast to this, the parts of the models involving difficult to evaluate mathematical expressions—for low-power, low-resource hardware—must be simplified, while preserving as much preciseness as possible. This will be a major part of future work.

In addition, we will focus on self-configuration, i.e., nodes should become capable to determine and update the model parameters on their own. We will also equip our hardware with an effective charging circuit and derive models for estimating incoming power. Finally, these models will be combined with the discharging ones, thus yielding a sophisticated base for energy-aware task scheduling.

Acknowledgment

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