Poster: Towards an Accurate Lifetime Estimation of Battery-Free Sensor Nodes Powered by Supercapacitors

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Abstract

Recent advances in energy-harvesting and low-power components have led to the emergence of battery-free sensor nodes that rely solely on ambient energy and environmental-friendly supercapacitors as energy storage. Accurately estimating the lifetime of these sensor nodes is crucial to guarantee that they can also operate in periods where no ambient energy is available, yet very complex. In this poster, we show experimentally that off-the-shelf supercapacitors have large capacitance tolerances and exhibit complex discharging characteristics due to leakage and charge-distribution effects. We argue that these cannot be neglected and that empirical data profiling the characteristics of supercapacitors is essential towards an accurate estimation of the system's lifetime.

1 Introduction and Motivation

The prospect of maintenance-free, everlasting operation has attracted a lot of research interest in the IoT community and resulted in the development of battery-free sensor nodes. The latter often employ a small capacitor that buffers energy harvested from environmental sources (e.g., light, vibration, or temperature) to execute single tasks. As the harvested energy highly varies over time, sensor nodes operate *intermittently*, i.e., they shut down after depleting the accumulated energy and wait until the capacitor has recharged. Consequently, these systems can only operate if energy can be harvested, and are limited to use cases where the events of interest occur when energy is available. However, many real-world applications (such as alarm systems) require *perpetual* operation, i.e., even when no ambient energy is present.

To support perpetual systems while adhering to the idea of sustainable, battery-free operation, *supercapacitors* (or *supercaps*) are often used as energy storage. In contrast to batteries, supercaps are not constrained in the number of (re-)charge cycles and can thus effectively provide unlimited operation, while offering a magnitude higher capacities than conventional capacitors. Moreover, they overcome the shortcomings of batteries, which are typically bulky, costly, environmental unfriendly, and require frequent replacement or disposal. While these properties make supercaps appealing and suitable to realise long-lasting battery-free sensor nodes, their deployment involves a major challenge: supercaps exhibit leakage currents in the order of µA that may exceed the average power consumption of the sensor node itself [5].

Such leakage currents, as well as the available energy stored in the supercap, strongly depend on the capacitor model and on the charging time, leading to large variations in the achievable lifetime. Consequently, estimating the lifetime of a sensor node powered by a supercap is not trivial, yet very important: overestimating it causes an *under-provisioning* of the provided storage capacity and hence may lead to accidental power-failures. Underestimating, on the other hand, leads to *over-provisioning* of the capacity and introduces several disadvantages associated with larger capacitances, such as higher costs, larger form factors, and limited efficiency (e.g., due to increased leakage and longer charging times).

An *accurate* estimation of the system's lifetime hence allows to dimension the capacitance of a supercap in order to minimize costs, form factors, and inefficiencies, while ensuring sustained operation for a given time. In addition, it yields the basis for energy-awareness, which allows devices to optimize their operation depending on the incoming energy.

In existing works, however, supercap's characteristics are often neglected, or only specific aspects are considered separately when estimating the system's lifetime (e.g., the impact of leakage currents [5] or charging times [3]). In this poster, we highlight the impact of these properties on the achievable lifetime (§ 2) and further discuss how to integrate them in the lifetime estimation process of sensor nodes powered by supercaps, outlining the associated challenges (§ 3).

2 Supercapacitors Are Not All Equal

To emphasize how the supercap's characteristics affect a system's lifetime, we measure experimentally the lifetime of an MSP430-based sensor node (i.e., how long it operates from the supercap's power without incoming energy) using four different supercaps with the *same* rated capacitance (220 mF) and voltage (5.5 V). To this end, after charging each supercap for a certain time, we monitor its voltage and derive the sensor node's lifetime, assuming that the MSP430 can run between 1.8 and 3.3 V. Fig. 1(a) shows that there are significant

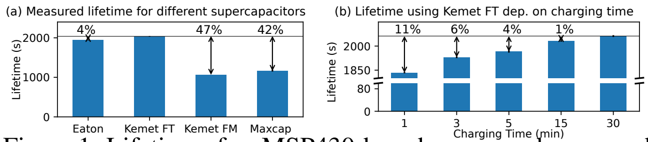

Figure 1: Lifetime of an MSP430-based sensor node powered by different supercapacitors (a) and by a single supercapacitor charged for different amounts of time (b).

differences in the achievable lifetime among the four supercap models. Although each of them has been charged equally (15 minutes to 3.3 V), we observe differences in lifetime by up to 47%. As we show in § 3, these differences stem, among others, from diverse capacitances and self-discharge characteristics. Furthermore, Fig. 1(b) highlights that the available energy cannot be determined solely from the capacitor's voltage: when charging a supercap to the very same voltage level for different times, the lifetime varies by up to 11%.

3 Lifetime Estimation

We now discuss how to estimate a sensor node's expected lifetime by conservatively assuming zero incoming energy. Zhu et al. [5] propose to estimate the lifetime in an iterative process based on (i) the *available energy* stored in the capacitor, (ii) the energy lost due to *leakage* currents, and (iii) the *consumed energy* of the sensor node.

The estimation process starts at $t_0 = 0$ with the currently stored energy $E_{cap}(0)$. For each iteration step n, the remaining energy after a time-window T can be computed using

$$E_{cap}((n+1)T) = E_{cap}(nT) - (E_L(nT) + P_C(nT)T) \quad (1)$$

where E_L correspond to the leaked energy and P_C to the consumed power, which is assumed to be constant within T. Once E_{cap} reaches its minimum value, such that the next iteration would lead to a power failure of the sensor node (i.e., if $E_{cap}((n+1)T < E_{min})$, the iteration process stops and nT yields the expected lifetime.

The accuracy of the lifetime estimation thus highly depends on the modelling of the parameters E_{cap}, $E_L(t)$, and $P_C(t)$, which is non-trivial and involves several challenges.

Estimating $E_{cap}(0)$. The energy stored in an ideal capacitor depends on its capacitance and terminal voltage V_{cap}, and is given by $E = \frac{1}{2}CV_{cap}^2$. However, as shown in Fig. 1 and highlighted in [3], the equation does not hold true in practice, as the amount of stored energy can differ at the same voltage level due to charge distribution effects. Moreover, the rated capacitance of commercial supercaps has typically large tolerances from -20 to $+80$% and is either determined using the charge- or discharge method [1]. Using the latter, we obtain the capacitance of the four supercaps studied in Fig. 1. Fig. 2(a) shows that the actual value indeed differs greatly: Kemet FT has almost twice the capacitance of Kemet FM.

Estimating $E_L(t)$. The different lifetimes observed in Fig. 1(a) do not only stem from the diverse capacitances, but are also influenced by the self-discharge characteristics (i.e., leakage) of the supercapacitor model. The information provided in datasheets is typically not sufficient for accurate modelling, as they often specify leakage currents rather vague for entire product families (e.g., 1-25μA [1]) or determine it after charging periods of >24 hours, which is not feasible for energy harvesting devices. It is thus necessary to model the

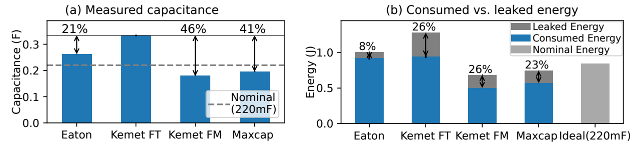

Figure 2: Measured capacitance (a) and energy leakage (b).

leakage behaviour based on experimental data. Since leakage is based on losses in the internal structure of the capacitor, it cannot be determined directly, but has to be derived from the measured capacitor voltage and consumed energy [4]. Using a constant discharge current I_C and by monitoring the supercap's voltage V_{cap}, it is possible to calculate the difference in stored energy for a given time interval T using

$$\Delta E_{cap} = E_{cap}(0) - E_{cap}(T) = \frac{C}{2}(V_{cap}(0)^2 - V_{cap}(T)^2) \quad (2)$$

and to estimate the consumed energy using

$$E_C = \int_0^T P_C(t)\,dt \approx P_C T = \frac{V_{cap}(0) + V_{cap}(T)}{2} I_C T. \quad (3)$$

The remaining energy that has not been consumed must have dissipated from the capacitor and gives the leaked energy $E_L = \Delta E_{cap} - E_C$. We investigate the leakage behaviour of the four supercaps and retrieve the energy profile while discharging them to from 3.3 to 1.8 V at I_C = 220 μA. Fig. 2(b) highlights that (i) the amount of leaked energy is rather high (up to 26%) and that (ii) the difference between the supercap models is significant (e.g., 8% vs. 26% for Eaton and Kemet FT, respectively). This explains why the retrieved capacitance value does not directly correlate with the observed lifetime and emphasizes that the leakage characteristics *must* be taken in account for an accurate lifetime estimation.

Estimating $P_C(t)$. Supercap-powered sensor nodes, in contrast to battery-powered devices, have to deal with large variations in operating voltage (e.g., due to the depletion of the stored energy). Ahmed et al. [2] have shown that fluctuations affect the clock speed and power consumption of MCUs based on digitally controlled oscillators (which are typically employed in low-power designs). We believe that accurate modelling of these dependencies is required to determine the power consumption (and consequently the expected lifetime) in a precise way, and will study them in detail in future work.

4 Outlook

In this poster, we have highlighted that the lifetime estimation of sensor nodes powered by supercapacitors is non-trivial, must rely on empirical data, and is worth further investigations. We thus plan to build a low-cost tool that allows to accurately and automatically characterize the discharging behaviour of supercapacitors at runtime, in order to foster the development and adoption of perpetual battery-free systems.

5 References

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