Lifetime Prediction for Supercapacitor-powered Wireless Sensor Nodes

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GI/ITG Fachgespräch "Sensornetze" (FGSN '09)
13. August 2009

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Possible Power-Supply Techniques

- Batteries
- Rechargeable Batteries
- Rechargeable Batteries + Energy Harvester
- SuperCap + Energy Harvester

Advantages of SuperCaps

- Small and light-weighted
- Long lifetime
- Virtually unlimited charge/discharge cycles
- High power density
  $\longrightarrow$ high peak currents
- Simple charging circuit
- Easy estimation of stored energy

Energy Awareness

Knowledge of available energy $\Rightarrow$ Energy Awareness

Benefits for known task energy costs

- Lifetime prediction
- Efficient use of available energy resources, e.g.,
  - Energy-aware scheduling
  - Energy-aware network-wide decisions
    $\longrightarrow$ routing, clustering, ...
- Low risk of energy starvation
- Perpetual power supply

The Prototype

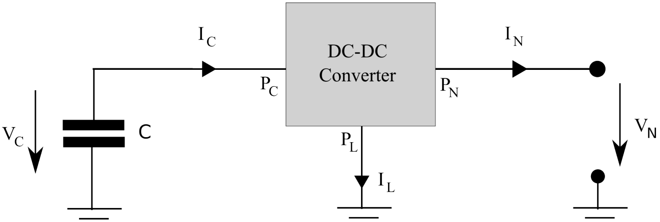
- Small but sufficient solar cell
- SuperCap as energy buffer
- Highly efficient DC-DC converter for low currents

Topic of the Day

Lifetime Prediction

Theory in Praxis

Simple Model – Overview



$$P_{\mathrm{N}} = P_{\mathrm{C}} - P_{\mathrm{L}} = \eta \cdot P_{\mathrm{C}}$$

Simple Model – The Solution

$$T_{\text{life}} = \frac{\eta C}{2 P_{\text{N}}} \left(V_{\text{C},0}^2 - V_{\text{min}}^2 \right)$$

▷ Details

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It's that simple, isn't it?

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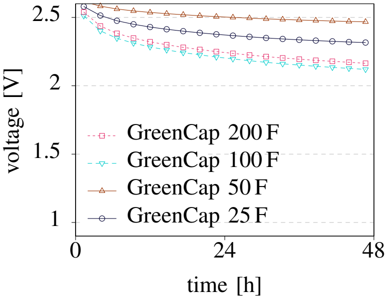
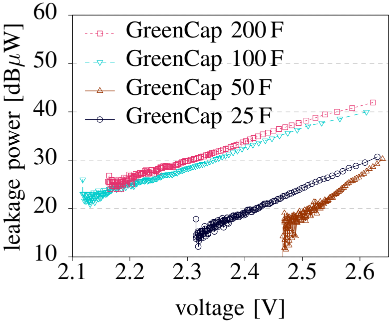
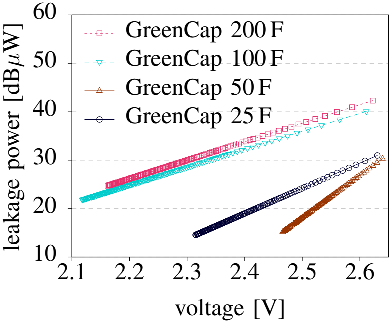
Self Discharge

Maybe not *that* simple — mind the SuperCap self discharge!



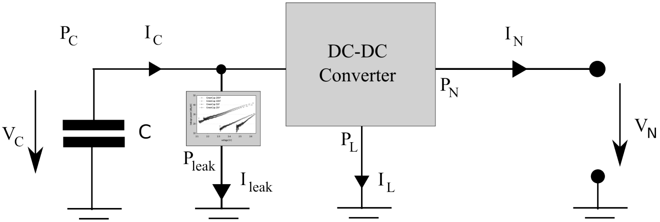
Leakage Power





$$P_{leak} \approx P_0 \cdot \exp(\alpha V_C)$$

Refined Model – Overview



$$P_{\mathrm{N}} = P_{\mathrm{C}} - P_{\mathrm{L}} - P_{\mathrm{leak}} = \eta \cdot P_{\mathrm{C}} - P_{\mathrm{leak}}$$

Refined Model – The Solution

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

▷ Details

Refined Model – The Solution

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

▷ Details

Refined Model – The Solution

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▷ Details

It's quite ugly, isn't it?

Evaluation

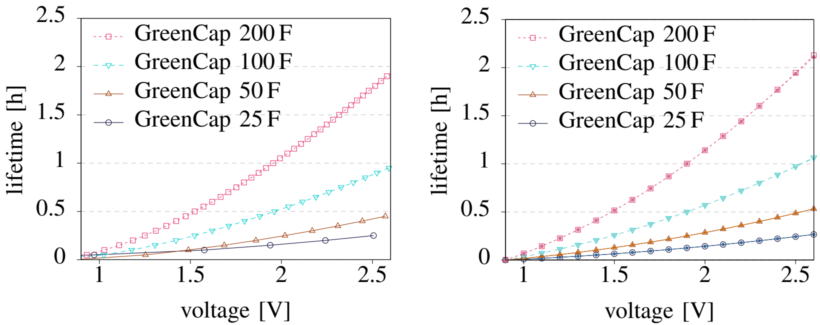
Goal:
Compare the simple and refined models with real behavior

Basis:

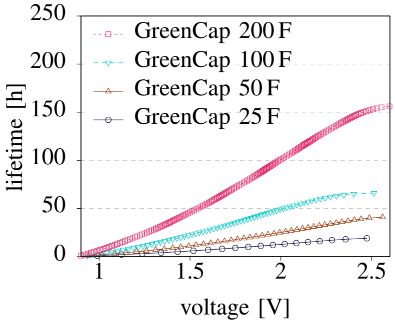
- Two manufacturers (Samwha GreenCaps and Panasonic GoldCaps)
- Capacitances from 22 F to 200 F
- Three duty cycles: ϑ = 1%, 10%, 100%
- Periodic measurement of SuperCap voltage

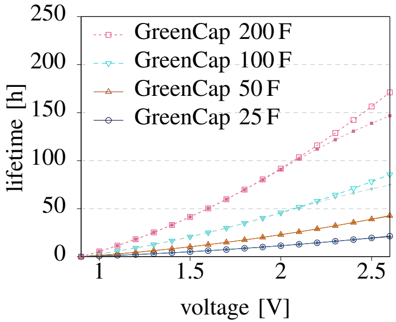
▷ More

Evaluation – 100% Duty Cycle



Evaluation – 1% Duty Cycle





Summary

What we have seen:

- Linear dependency between capacitance and lifetime
- Simple model sufficient for low V_C or high η
- Refined model needed for high V_C and low η

What you have not seen:

- Parameters influence predictions (actual C, η, P_N)
- The dilog can be neglected

Conclusion

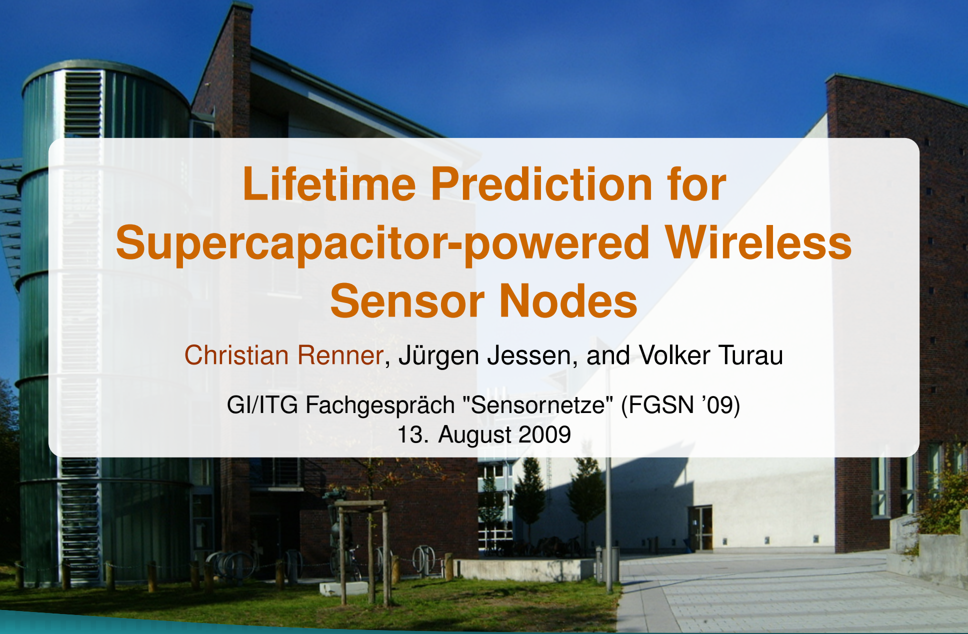
After the first steps we know:

- SuperCaps serve as sufficient energy buffers
- Simple and refined model for lifetime prediction exist
- Models trade off precision against simplicity
- Model parameters need to be determined

Future Work

But it's a long way ...

- Consider temperature and SuperCap aging effects
- Simplify calculations for the refined model
- Develop a self-configuring software module
- Improve the charging circuit
- Derive models for estimation of incoming power



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Simple Model – The Math

The model:

$$P_\mathrm{N} = \eta \cdot V_\mathrm{C} \cdot I_\mathrm{C}$$

The SuperCap as a source:

$$I_\mathrm{C} = -C \cdot \dot{V}_\mathrm{C}$$

The result:

$$P_\mathrm{N} = -\eta \cdot V_\mathrm{C} \cdot C \cdot \dot{V}_\mathrm{C}$$

The consequence:

$$\int_{t_0}^{t_0+T_\mathrm{life}} \mathrm{d}t = -\frac{\eta C}{P_\mathrm{N}} \int_{V_{\mathrm{C},0}}^{V_\mathrm{min}} V_\mathrm{C} \,\mathrm{d}V_\mathrm{C}$$

▷ Back

Refined Model – The Math

The model:

$$P_N = \eta \cdot V_C \cdot I_C + P_0 \cdot \exp(\alpha V_C)$$

The SuperCap as a source:

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

The result:

$$P_N = -\eta \cdot V_C \cdot C \cdot \dot{V}_C - P_0 \cdot \exp(\alpha V_C)$$

▷ Back

Numerical Leakage Power Analysis

$$E(V_\mathrm{C}) = \frac{C V_\mathrm{C}^2}{2} \Rightarrow P_\mathrm{leak}(V_\mathrm{C}) \approx \frac{\Delta E(V_\mathrm{C})}{\Delta t} = \frac{C \Delta V_\mathrm{C}^2}{2 \Delta t}$$

Evaluation – Assumptions

- $P_{\mathrm{N}} = V_{\mathrm{N}} \left(\vartheta \cdot I_{\mathrm{N,act}} + (1 - \vartheta) \cdot I_{\mathrm{N,sleep}} \right)$
  where $V_{\mathrm{N}} = 3.3\,V$, $I_{\mathrm{N,act}} = 20\,mA$, and $I_{\mathrm{N,sleep}} = 20\,\mu A$
- $\eta = \vartheta \cdot \eta_{\mathrm{act}} + (1 - \vartheta) \cdot \eta_{\mathrm{sleep}}$
  where $\eta_{\mathrm{act}} = 85\%$ and $\eta_{\mathrm{sleep}} = 75\%$

▷ Back

Evaluation – 10% Duty Cycle