# CapLibrate: Self-Calibration of an Energy Harvesting Power Supply with Supercapacitors

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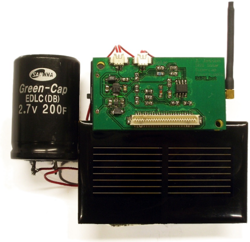
# Introduction

# Modern Wireless Sensor Nodes

- Low-Power Components
- Energy Harvesting Power Supply
- Energy Buffer



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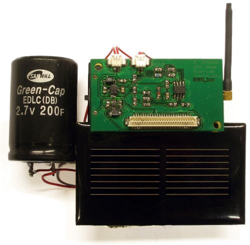


Unattended Operation $\Rightarrow$ Power Management

# 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 operation

# SuperCaps – the Good News


- Small and light-weighted
- Long lifetime
- Virtually unlimited charge/discharge cycles
- Simple charging circuit
- Easy estimation of stored energy

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

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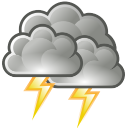
# The Bad News



**Capacity** $C$ depends on

- manufacturing variation
- temperature
- age

**Circuit efficiency** $\eta$ depends on

- actual DC-DC-efficiency
- manufacturing variation
- part tolerances
- hardware revisions (different parts)

Manual calibration infeasible in large networks

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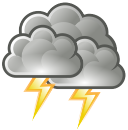

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# Dish of the Day

## Self-Calibration

Theory in Praxis

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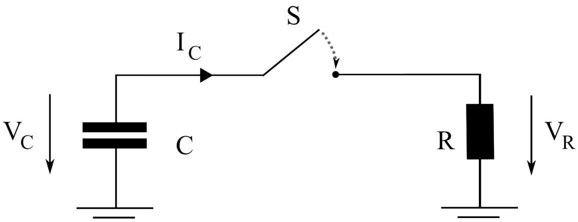
# Analytical Assessment

# Resistance Discharging

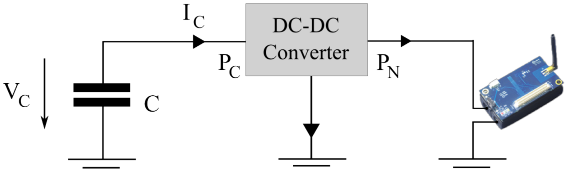



$$V_{\mathrm{C}} = V_{\mathrm{C}0} \cdot \mathrm{e}^{-\frac{\Delta T}{RC}}$$

# Resistance Discharging – Solution

$$C = \frac{\Delta T}{R} \cdot \ln^{-1}\left(\frac{V_{\mathrm{C}0}}{V_{\mathrm{C}}}\right)$$

# Converter Discharging




$$E_C = E_{out} \iff \frac{C \cdot \left(V_{C0}^2 - V_C^2\right)}{2} = \frac{\Delta T \cdot P_N}{\eta}$$

# Converter Discharging – Solution

$$C = \frac{2 \cdot \Delta T \cdot P_{\mathrm{N}}}{\eta \cdot \left( V_{\mathrm{C}_0}^2 - V_{\mathrm{C}}^2 \right)}$$

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# Evaluation

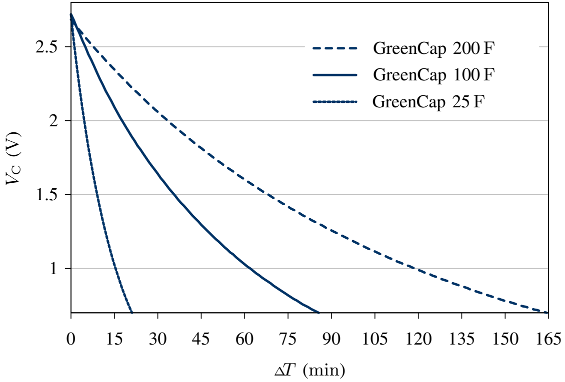
# Environment

- Crossbow IRIS node with TinyOS 2.1
- Sampling of $V_{\mathrm{C}}$ via node's ADC
  Averaging 4 readings to reduce noise
- Sending result via radio to PC
- Samwha GreenCaps: $C = 25\,\mathrm{F}, 100\,\mathrm{F}, 200\,\mathrm{F}$
- Initial value of $V_{\mathrm{C}} = 2.7\,\mathrm{V}$
- Reference voltages $V_{\mathrm{C}0} = 1.5\,\mathrm{V}, 2.0\,\mathrm{V}, 2.5\,\mathrm{V}$

# Discharging Setups

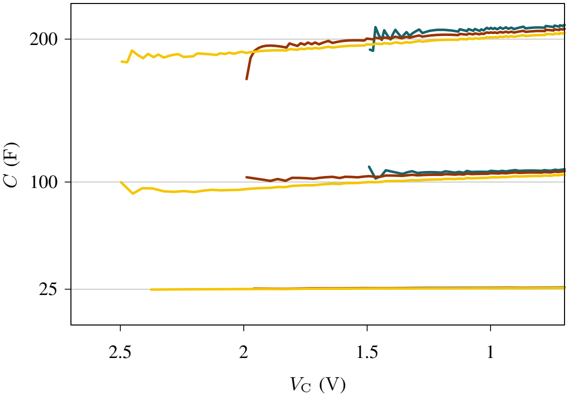
1. **Stand-alone Resistance Discharging**
   - $R = 36.1\,\Omega$
   - Node powered by battery
2. **Combined Resistance Discharging** ▷ Math
   - $R = 35.6\,\Omega$, switched via MOSFET
   - Node powered by SuperCap
   - $P_{\mathrm{N}} < 100\,\mu\mathrm{W}$ (sleep mode)
3. **Converter Discharging**
   - Node powered by SuperCap
   - $P_{\mathrm{N}} = 51.2\,\mathrm{mW}$ (radio on)
   - $\eta \approx 85 - 91\%$ for $V_{\mathrm{C}} = 1.5 - 2.5\,\mathrm{V}$

# Stand-alone Discharging: Voltage



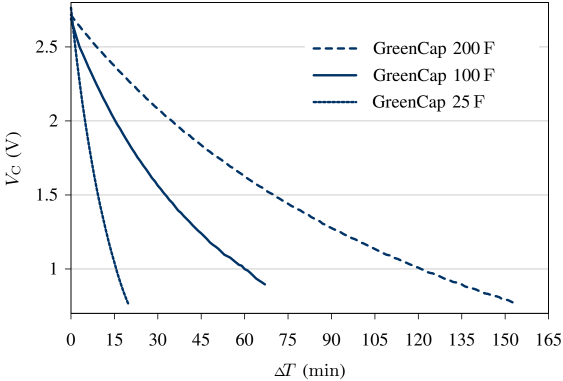

- Linear influence of $C$
- Exponentially decreasing $V_C$

# Stand-alone Discharging: Capacitance



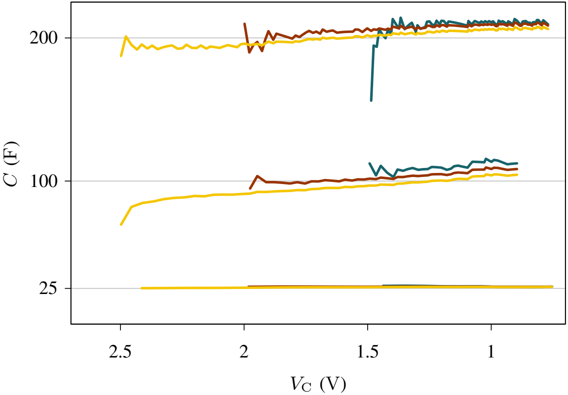

- $C$ slightly increasing for smaller $V_\mathrm{C}$
- Notable influence of sampling errors for $\Delta V_\mathrm{C} < 0.1\,\mathrm{V}$

# Combined Discharging: Voltage



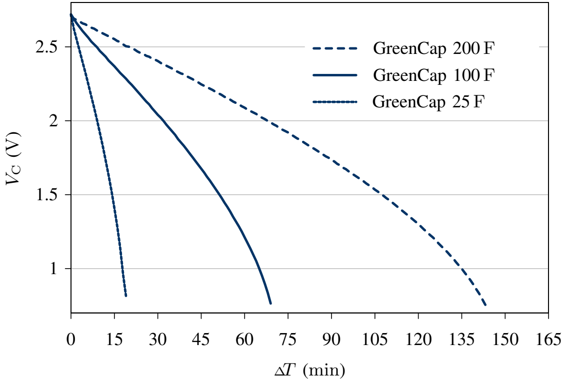

- Node power does not influence measurement significantly

# Combined Discharging: Capacitance



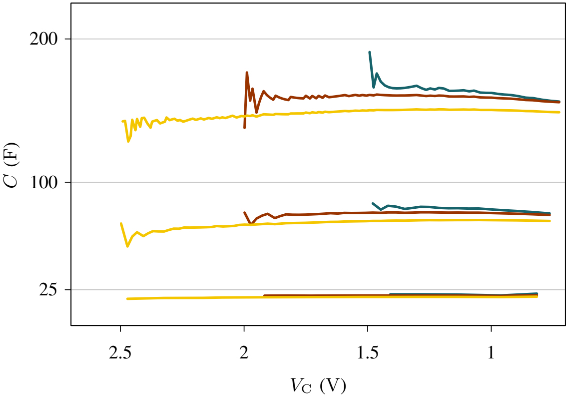

- Comparable results as before ⇒ approach feasible

# Converter Discharging: Voltage



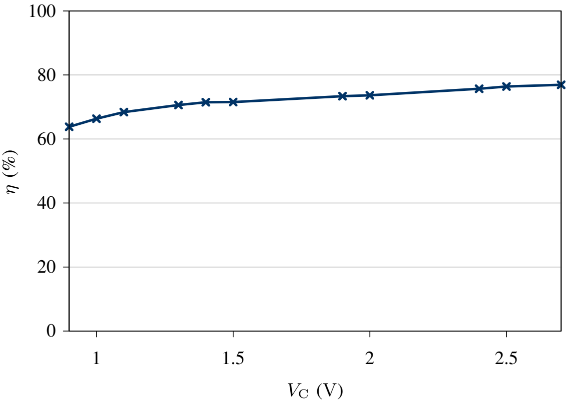

- Linear influence of *C*
- Square-root shape

# Converter Discharging: Capacitance



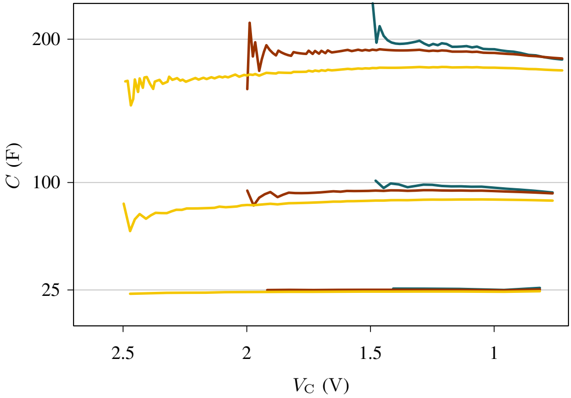

- Massive underestimation of $C$
- Heavy influence of $V_{C0}$

# Circuit Efficiency




- Circuit efficiency considerably lower than converter efficiency

# Converter Discharging: Capacitance Revisited




- Still heavy influence of $V_{\mathrm{C}0}$: Large influence of leakage (discharging current lower than for resistance approach)

# Summary

- Capacity estimation using resistance discharging is practicable
  - Low voltage drop needed ($\Delta V_{\mathrm{C}} \approx 0.1\,\mathrm{V}$)
  - Quick measurement possible ($\Delta T < 10\,\mathrm{min}$ for $C = 200\,\mathrm{F}$)
  - Good results
- Converter discharging has problems
  - Low current leads to high influence of leakage current
  - Good results only for low $V_{\mathrm{C}}$
  - but can be used for efficiency determination

# Roadmap for Online Capacity Determination

## Initial estimation

1. Capacity determination
   1.1 Wait for appropriate $V_{\mathrm{C}}$ (e.g., $2\,\mathrm{V}$)
   1.2 Put node into sleeping mode, enable resistance discharging
   1.3 Wait until discovering needed $\Delta V_{\mathrm{C}}$ (e.g., $0.1\,\mathrm{V}$)
   1.4 Estimate capacity $C$
2. Efficiency determination
   2.1 Disable resistance discharging
   2.2 Switch to high power mode
   2.3 Wait until discovering needed $\Delta V_{\mathrm{C}}$ (e.g., $0.1\,\mathrm{V}$)
   2.4 Estimate efficiency $\eta$

**Maintenance** Repeat estimation in service intervals or when performance of (lifetime) prediction degrades

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# Conclusion

# Conclusion

- Refinement of lifetime prediction by
  - estimating and updating capacity
  - tracking actual circuit efficiency
- Proposition of two possible methods
- Analytical and practical evaluation on real hardware
- Starting point for self-calibration of an energy-harvesting power-supply

# Future Work

- Convert knowledge into software
- Run field tests
- Refine algorithm
- Flip the coin: assess prediction of harvested energy

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# Combined Discharging

▷ Back

Energy obtained from SuperCap

$$\Delta E_{\mathrm{C}} = \frac{1}{2} C \left( {V_{\mathrm{C}0}}^2 - V_{\mathrm{C}}^2 \right) \tag{1}$$

Energy consumption of the converter

$$E_{\mathrm{out}} = \frac{\Delta T \cdot P_{\mathrm{N}}}{\eta} \tag{2}$$

Energy consumption of the resistor

$$E_R = \frac{{V_{\mathrm{C}0}}^2}{R} \int_0^{\Delta T} \mathrm{e}^{-\frac{2t}{RC}} \, \mathrm{d}t = \frac{C {V_{\mathrm{C}0}}^2}{2} \cdot \left( 1 - \mathrm{e}^{-\frac{2\Delta T}{RC}} \right) \tag{3}$$

With $\Delta E_{\mathrm{C}} = E_{\mathrm{out}} + E_R$

$$C \cdot \left( {V_{\mathrm{C}0}}^2 \cdot \mathrm{e}^{-\frac{2\Delta T}{RC}} - V_{\mathrm{C}}^2 \right) = \frac{2 \cdot \Delta T \cdot P_{\mathrm{N}}}{\eta} \tag{4}$$