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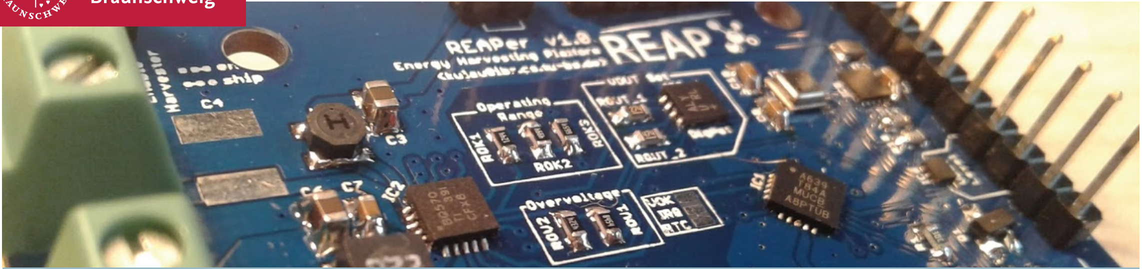


REAPer
Adaptive Micro-Source Energy-Harvester for Wireless Sensor Nodes

SenseApp 2017

Ulf Kulau, Daniel Bräckelmann, Felix Büsching, Sebastian Schildt and Lars Wolf, 09.10.2017
Technische Universität Braunschweig, IBR

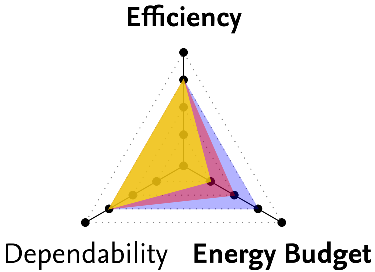
Towards more adaptive WSNs

WSNs in real environmental conditions

- Various parameters (especially temperatures) affect the characteristics of WSNs
  - **Dependability:** Efficiency of transceivers, HW faults, ...
  - **Efficiency:** Power dissipation, ...
  - **Energy budget:** Energy Harvesting, Energy storage, ...

Towards more adaptive WSNs

Project goal: Robust but efficient WSNs by adapting operation parameters



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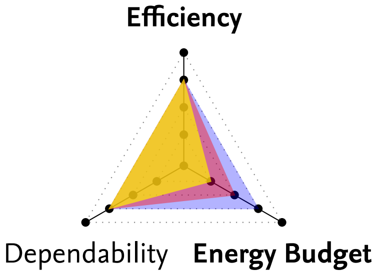

- Adaptive energy harvesting platform REAPer
  - **Energy harvesting:**
    → Varying energy budget
  - **Voltage scaling (undervolting):**
    → Adaptive energy efficiency

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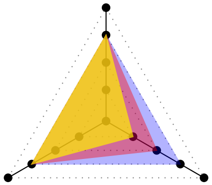

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Undervolting in WSNs – Background

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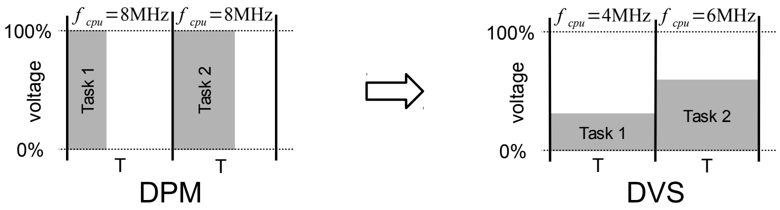

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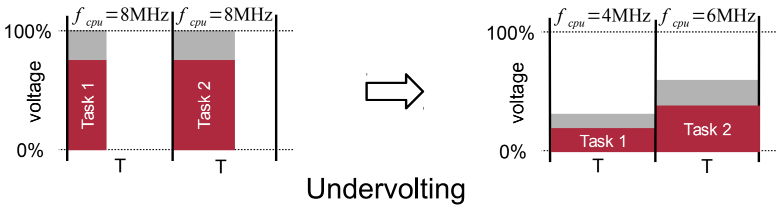
- DVS: Adapting f_{cpu} to current workload *and* scale $V(f_{cpu})$
- Undervolting: **Violate specifications** $V(f_{cpu}) \rightarrow V(f_{cpu}) - \Delta V$



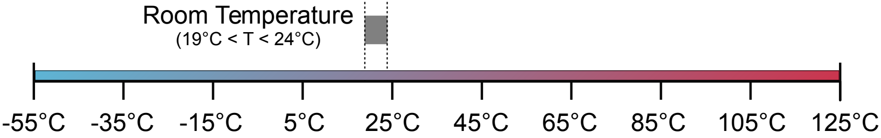
Undervolting in WSNs – Background

Legitimation to use undervolting

- Threshold Voltage V_{th} of CMOS is temperature-dependent

$$V_{th}(T) = V_{tho} + \alpha \cdot (T - T_0)$$

MCUs cover a widespread temperature range with a fixed $V(f_{cpu})$



$\rightarrow$ MCUs must be able to run below $V(f_{cpu})$ (under *normal* conditions)

Is this a *good* idea?

Undervolting will lead to a higher unreliability:

- Operating devices outside their specification
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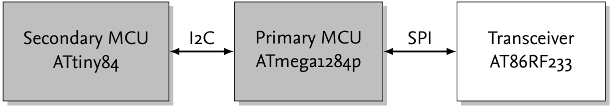
Our Perspective:

- WSNs need increased energy efficiency and offer fault tolerance (ideal)
- Fulfill WSN tasks even with limited energy budget!

IdealVolting – Adaptive undervolting scheme

IdealVolting implementation on undervolting capable node INGA v1.6.1

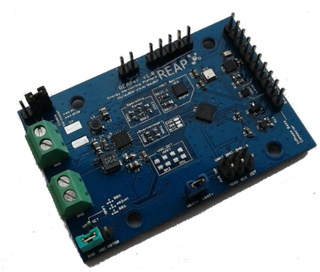


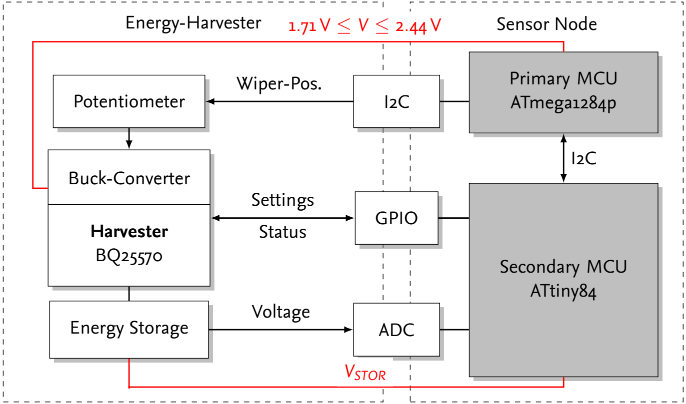
1. Control loop to ascertain ideal voltage levels
   → Find most energy efficient but reliable operating point individually
2. Supervised-Learning approach
   → Collect and predict ideal operating points

Kulau et.al., *IdealVolting – Reliable Undervolting on Wireless Sensor Nodes*, ACM Transactions on Sensor Networks (TOSN), 2016

Architecture of REAPer

Integrate IdealVolting to energy harvesting and vice versa...





Static current consumption of REAPer

Quiescent current of the entire REAPer platform

- Test conditions:
  - Energy Storage initially charged to $V_{STOR} = 5V$, no load at buck-converter

	Mean (nA)	Min (nA)	Max (nA)
Normal	567.23 ± 15.45	546.0	592.0
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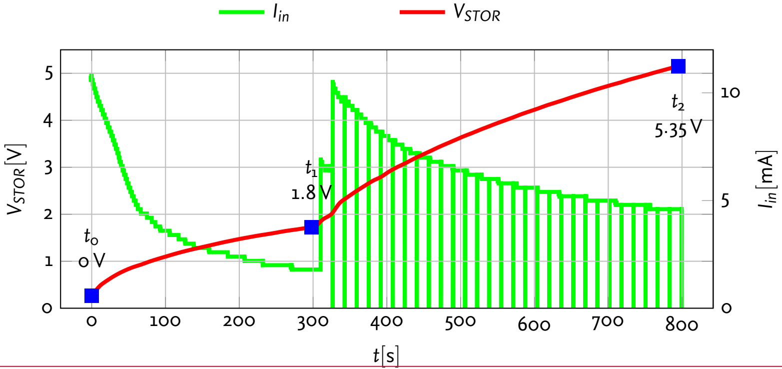
$\rightarrow$ Reasonable overhead below 1 µA

Charging characteristics

Exemplary charging curve at $V_{in} = 1000$ mV input voltage (Energy storage: Cap 1 F)

$t_{0\rightarrow 1}$: Cold start phase for $V_{STOR} \leq 1.8$ V with integrated charge-pump

$t_{1\rightarrow 2}$: Boost-Converter and duty-cycled MPPT is active for $V_{STOR} > 1.8$ V



Efficiency of the charging

Considering the energy that is stored by the capacitor ($C = 1\,\mathrm{F}$)

$$E = \frac{1}{2} \cdot CV^2 \tag{1}$$

Efficiency η can be derived by comparing stored Energy against input energy:

$$\eta = \frac{E}{E_{in_{t_0 \to t_2}}} \tag{2}$$

Where $E_{in_{t_0 \to t_2}}$ is based on...

- the time of charge $t_0 \to t_2$, the input current I_{in} and the input voltage V_{in}

Efficiency of the charging

Evaluation of the efficiency for different input Voltages 450 mV $\leq V_{in} \leq$ 1000 mV

	$t_{0\rightarrow1}$	$t_{1\rightarrow2}$	$t_{0\rightarrow2}$	
V_{in} [mV]	$\overline{E}_{in}$ [mWh]	$\overline{E}_{in}$ [mWh]	$\overline{E}_{in_{total}}$ [mWh]	η (%)
450	1.42	5.62	7.04	53.69
550	0.88	5.47	6.35	59.53
700	0.79	5.20	5.99	63.11
850	0.73	5.06	5.79	65.28
1000	0.71	5.04	5.75	65.74

- Higher input voltages lead to higher input power and higher efficiency

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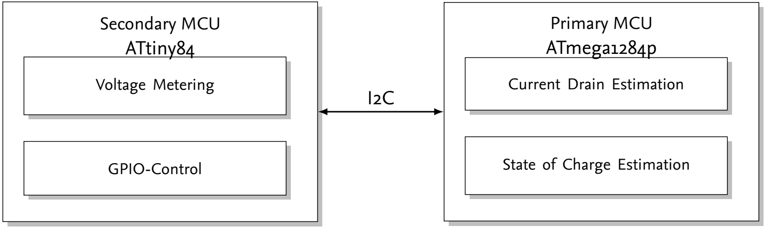
  $\rightarrow$ Advice for *How to connect your energy sources* (serial vs. parallel)

Software components (excluding IdealVolting)

SW Implementation on both MCUs

- Rudimentary functions on tiny secondary MCU
- More complex implementations on primary MCU



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Measurement of supply voltage $V_{cc} = V_{STOR}$ via bandgap reference V_{ref}

$$ADC = ADC_{max} \cdot \frac{V_{ref}}{V_{STOR}} \Leftrightarrow V_{STOR} = ADC_{max} \cdot \frac{V_{ref}}{ADC} \tag{1}$$

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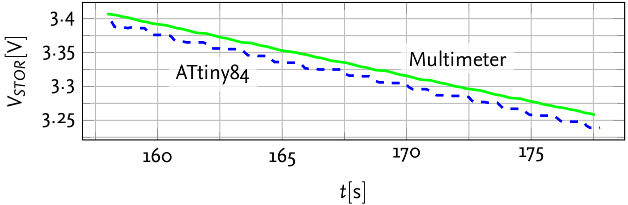

Result:
→ Measurement error below 1.5 %

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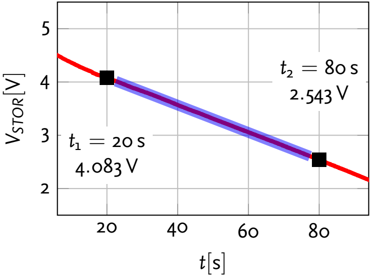
Further utilization of voltage metering

Assumption:

→ Energy storage is a capacitor (normal case)
→ Exploit the linear dis-/charge behavior



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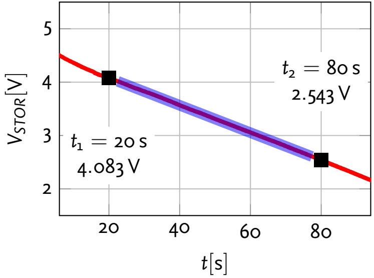
State of charge

- Relative state of charge is trivial

$$SoC(t)[\%] = \frac{V_{STOR}(t) - V_{min}}{V_{max} - V_{min}} \qquad (2)$$



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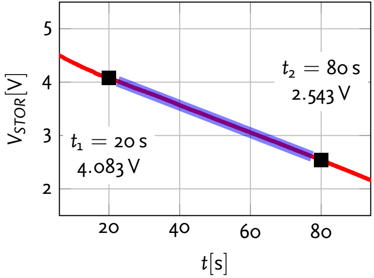
Current drain estimation

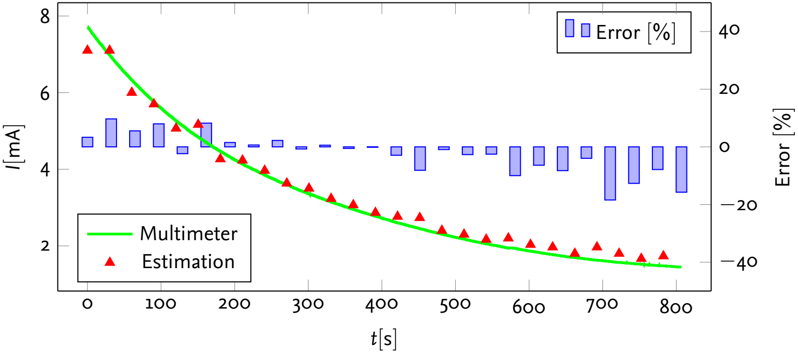
- Estimation of the average current consumption $\bar{I}$
- State of charge $Q(t)$ at two points in time

$$\bar{I} = \frac{\Delta Q}{\Delta t} = \frac{Q(t_2) - Q(t_1)}{t_2 - t_1} \qquad (2)$$



Evaluation – Current drain estimation

Result: Accuracy is suitable for a rough current drain estimation



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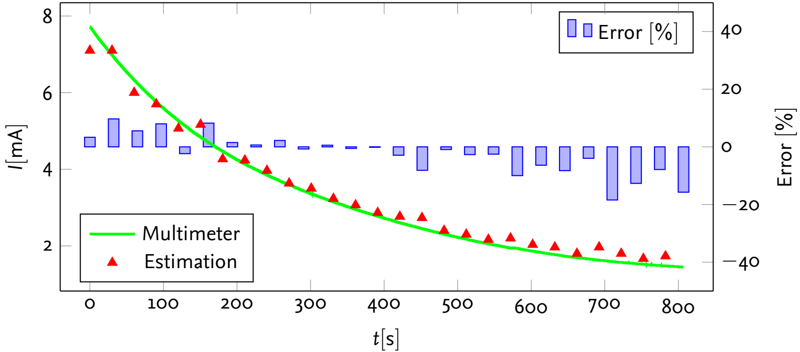
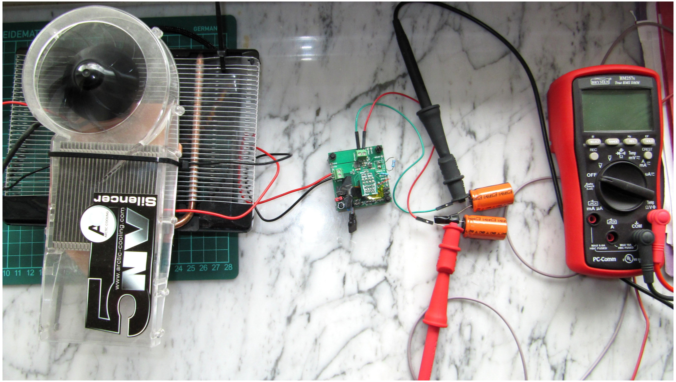


→ Limitation: Harvesting must be deactivated during measurement

First tests and future perspective



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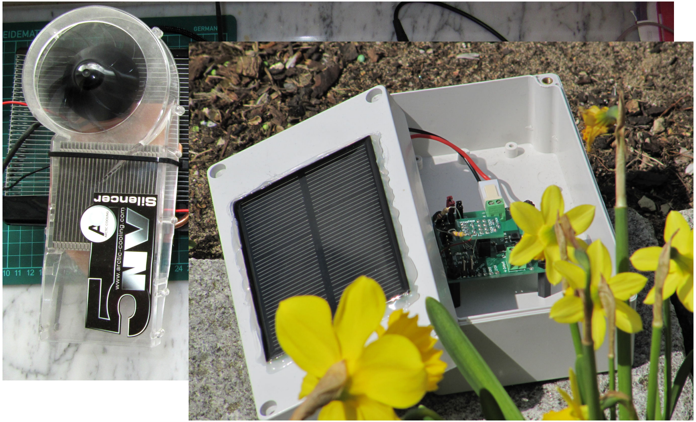

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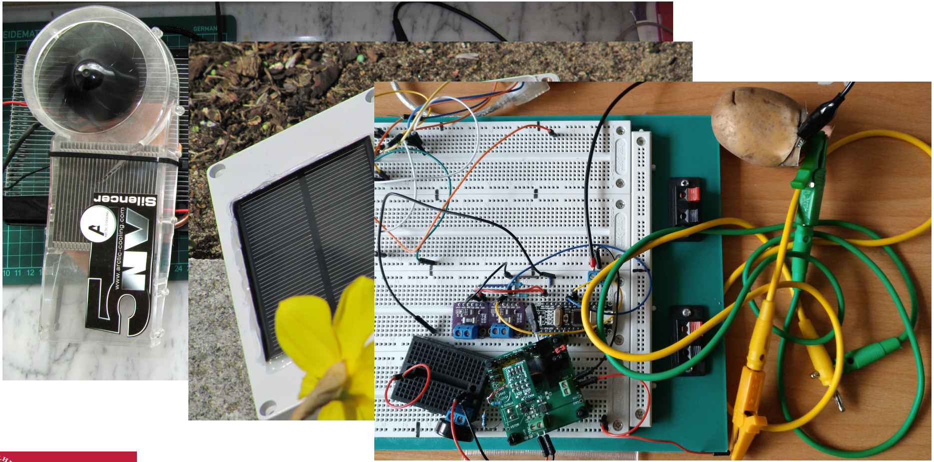

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  - Overhead, charging characteristics, Efficiency
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  - Voltage metering $\rightarrow$ State of charge, Current drain estimation

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Thank you for your attention! Questions?

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