Institute of Operating Systems
and Computer Networks

Technische
Universität
Braunschweig

Undervolting in Real World WSN Applications: A Long-Term Study

DCoSS 2016

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Lars Wolf, May 26, 2016
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Undervolting in WSNs – Background

Voltage Scaling increases energy efficiency significantly

- Dynamic power dissipation of CMOS $p_{dyn} = C_L \cdot f_{cpu} \cdot V^2$

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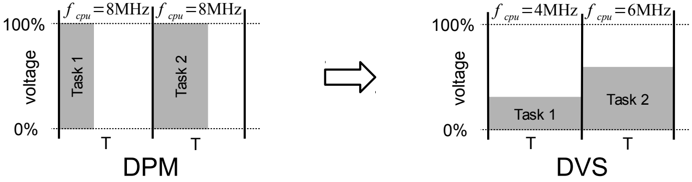
- DVS: Adapting f_{cpu} to current workload *and* scale $V(f_{cpu})$



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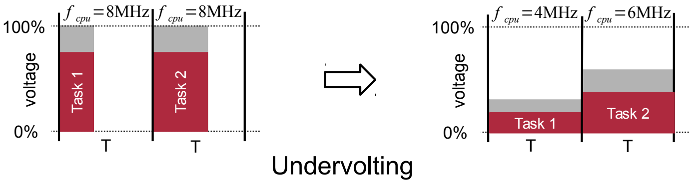
- Dynamic power dissipation of CMOS $p_{dyn} = C_L \cdot f_{cpu} \cdot V^2$
- DVS: Adapting f_{cpu} to current workload *and* scale $V(f_{cpu})$
- Undervolting: **Violate specifications** $V(f_{cpu}) \rightarrow V(f_{cpu}) - \Delta V$



Is this a *good* idea?

Undervolting will lead to a higher unreliability:

- Operating devices outside their specification
- Calculation errors, losses, resets, failures may affect the application

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Our Perspective:

- WSNs are designed to be *fault tolerant* per se (protocols, algorithms, applications, ...)
- WSNs need increased energy efficiency and offer fault tolerance (ideal)

IdealVolting – Adaptive undervolting scheme

Legitimation to use undervolting

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

$$V_{th}(T) = V_{th0} + \alpha \cdot (T - T_0)$$

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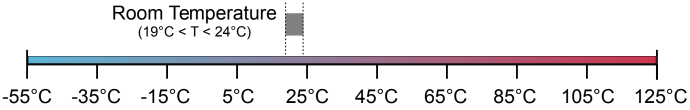
$$V_{th}(T) = V_{tho} + \alpha \cdot (T - T_o)$$

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)

IdealVolting – Adaptive undervolting scheme

IdealVolting implementation on every node

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

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Short Demo

Will undervolting affect real WSN applications?

→ Long-term study within an exemplary application area

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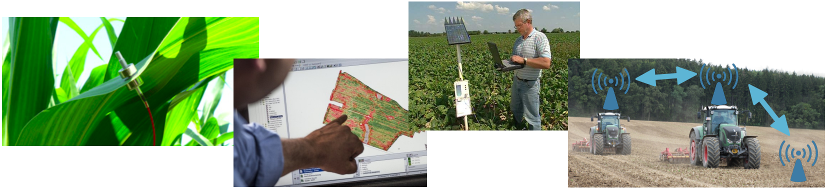
$\rightarrow$ Long-term study within an exemplary application area

Smart Farming – sensor networks in agriculture

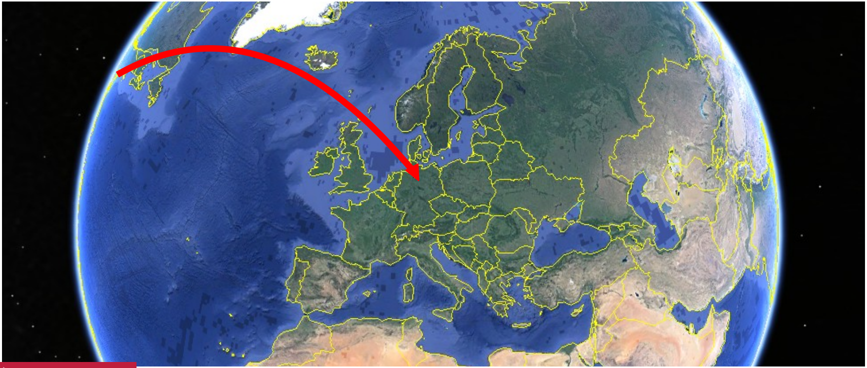


- A challenging application area, even without undervolting!
  - Harsh environmental conditions
  - Limited maintainability
  - Limited connectivity

PotatoNet – Outdoor WSN testbed

Joint venture with a potato crop research station

- Deployment of a WSN testbed on a trial field
- Enabling convenient outdoor WSN experiments



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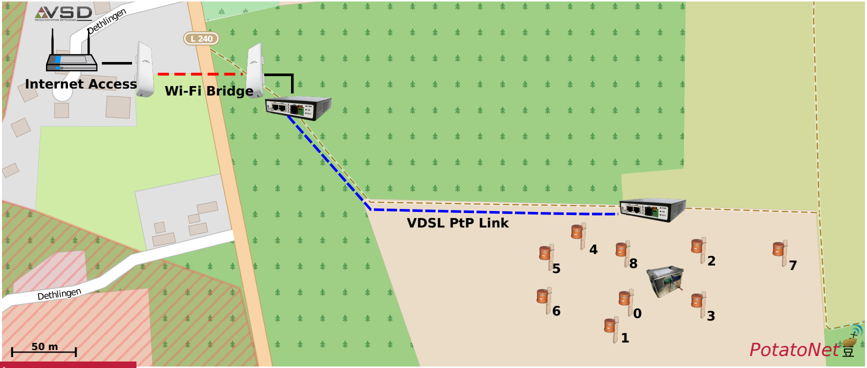
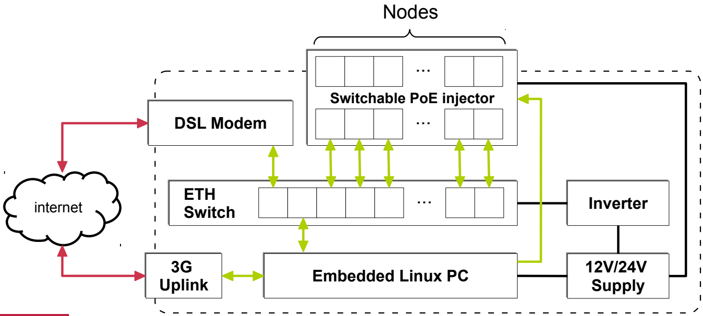


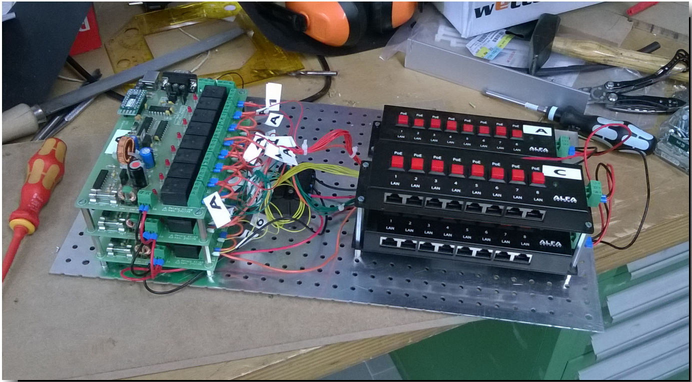
Central Box – Architecture

Components in central box

- Linux IPC (24V powered)
- Ethernet Switch and controllable, passive PoE Injectors
- Redundant internet uplinks



Central Box – Impressions



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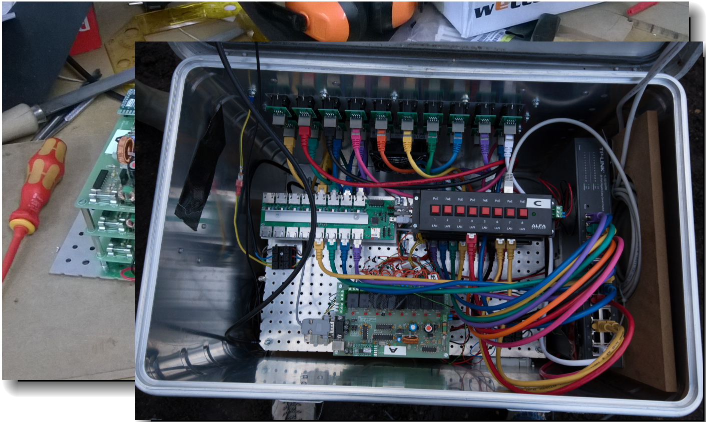
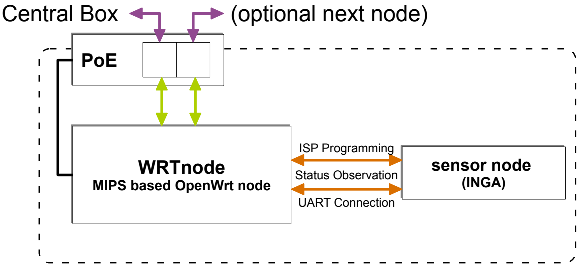


Central Box – Impressions

Field Node – Architecture

Components of the field node

- WRTnode (OpenWRT Linux Board)
- INGA 1.6.1 – Undervolting capable Wireless Sensor Node
- Powered via PoE → Concatenation of Nodes possible



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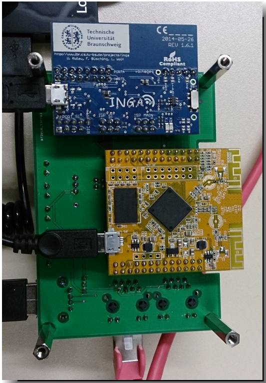

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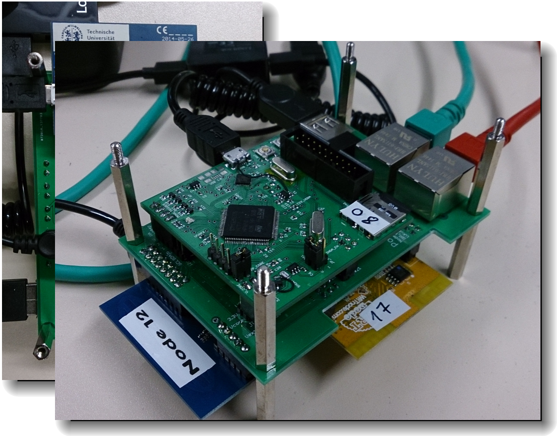

R.Hartung, U.Kulau and L.Wolf, *Distributed Energy Measurement in WSNs for Outdoor Applications*, SECON, 2016

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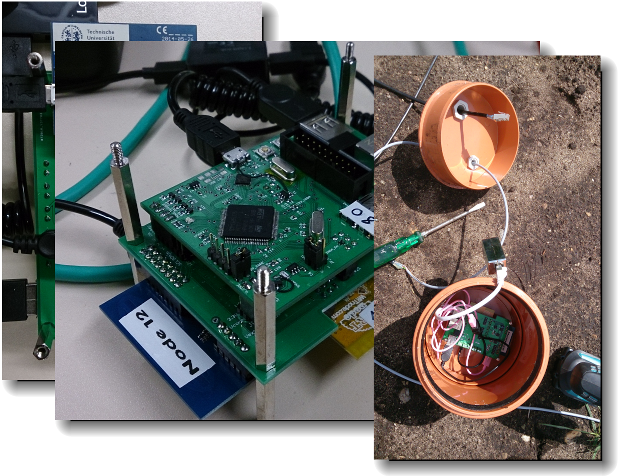
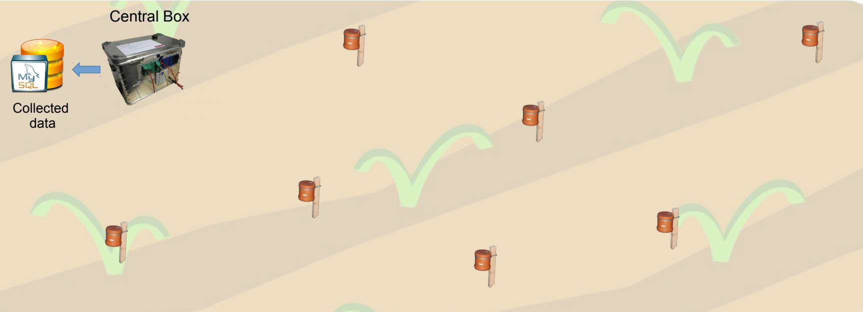


Field Nodes – Impressions

Long-term experiment

Goal: Evaluate an undervolted WSN vs. a normal powered WSN

- Central box coordinates the entire evaluation
- Alternating between undervolting and nominal voltage level



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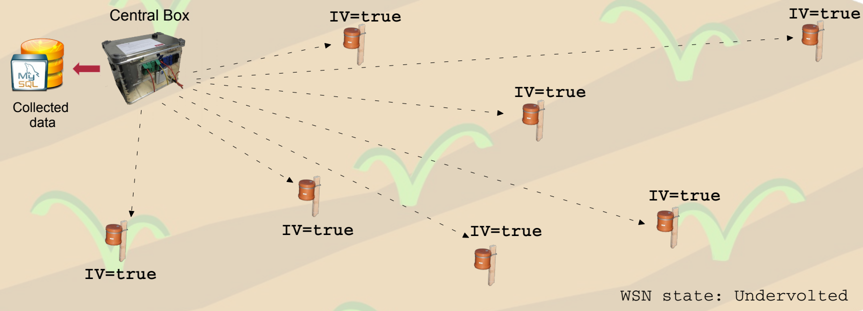

Step 1. Enable undervolting throughout the WSN

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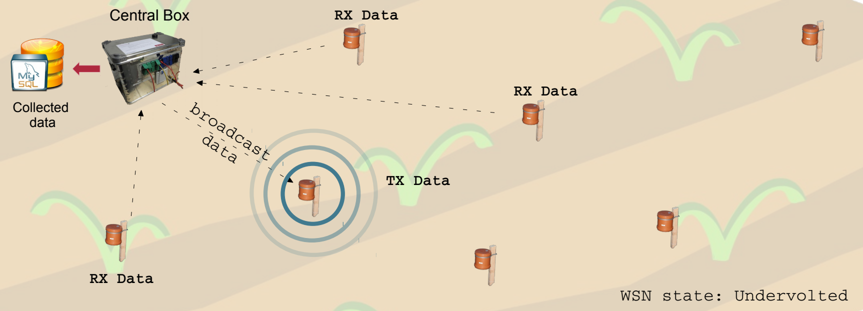

Step 2. One node at a time broadcasts a seq.no. (round robin)

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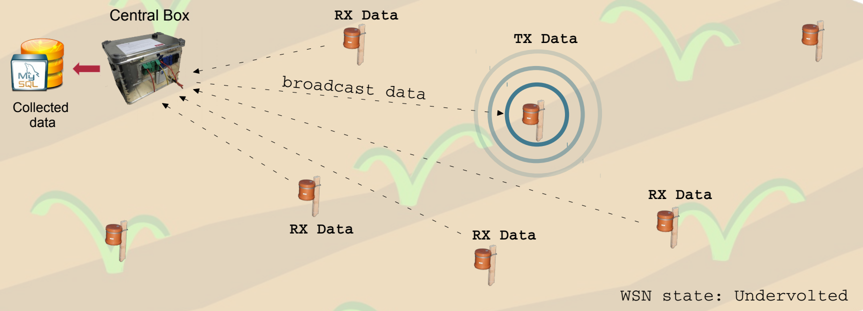

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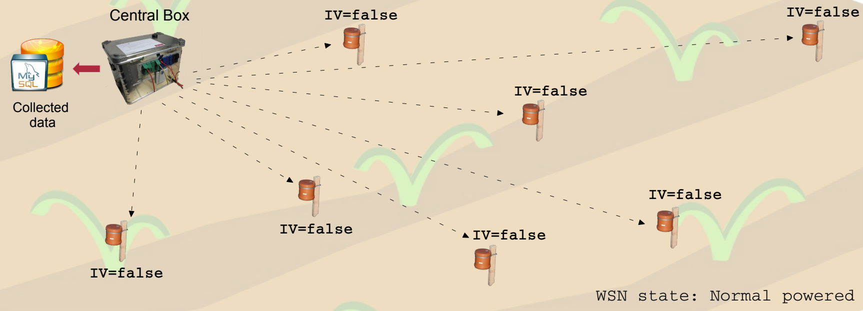

Step 3. Disable undervolting and repeat at step 2 (TX, round robin).

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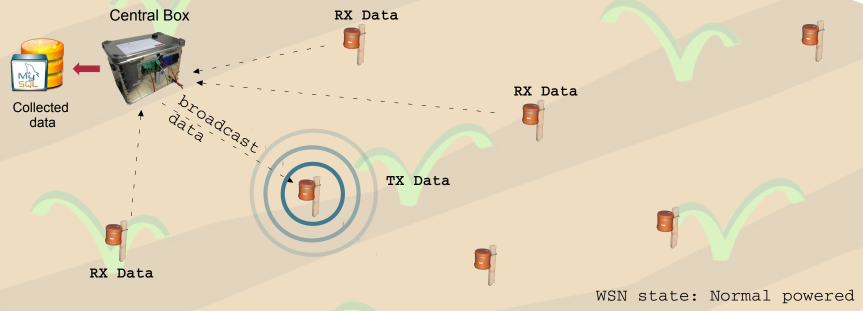

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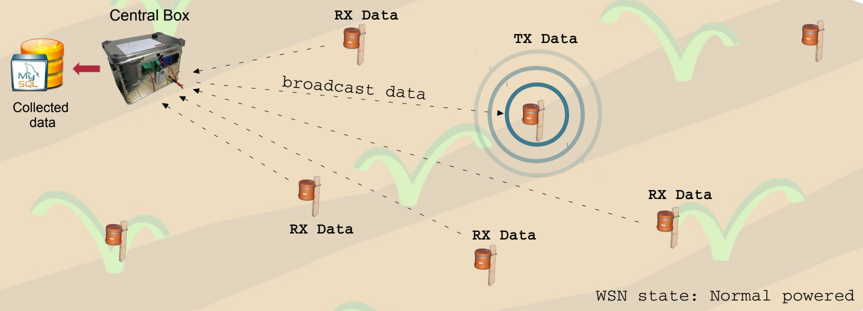

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Long-term experiment

- Duration 17.07.2015 - 18.11.2015 (4 months)
- 7.5 GB of collected data (voltage level, RX/TX (seq.no.), RSSI, temperatures, debug information, ...)[1]
- Changing scenarios and topologies (farming activities)

Field Deployment (with potato haulms)

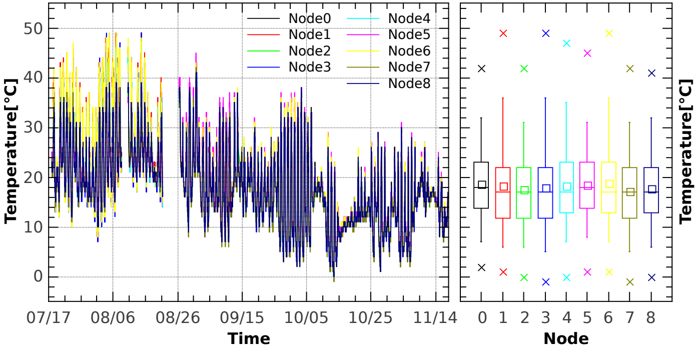
Field Deployment (without potato haulms)

Edge Deployment (potato harvest)

[1] https://www.ibr.cs.tu-bs.de/projects/potatonet/longterm.html

Experienced Temperatures

- Challenging environmental conditions
  - High fluctuation of the temperature T
  - Range between $-1^{\circ}C \leq T \leq 49^{\circ}C$



At first sight...

... **no difference** between the WSN states *undervolting* and *normal powered*

How to prove if undervolting affects a WSN?

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How to prove if undervolting affects a WSN?

- Calculate the difference between the parameters (e.g. Temperature, PRR, ...)

$$\Delta param = param_{i\nu} - param_n \tag{1}$$

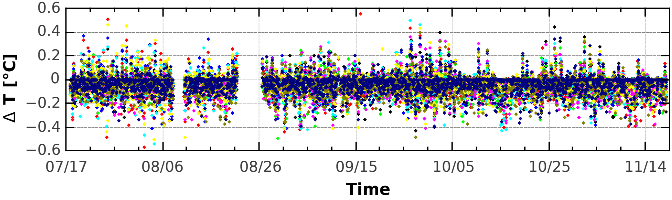
- Calculate the correlation between $\Delta param$ and the voltage level ν

$$r(\Delta param, \nu) = \frac{\sum_i \left(\Delta param_i - \overline{\Delta param}\right) \cdot (\nu_i - \overline{\nu})}{\sqrt{\sum_i \left(\Delta param_i - \overline{\Delta param}\right)^2 \cdot \sum_i (\nu_i - \overline{\nu})^2}} \tag{2}$$

Investigation – Quality of sensing

Quality of sensing

- Both WSN states experienced the same environmental conditions
  $\rightarrow$ Direct comparison is possible

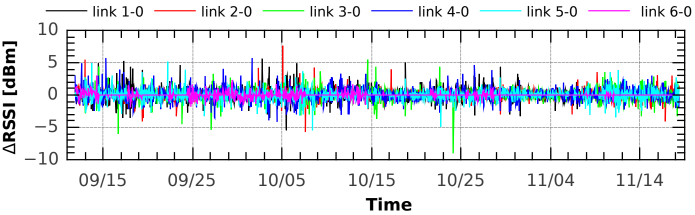


Overall result: No correlation between undervolting and the quality of temperature sensing can bee seen ($r(\Delta T, \nu)$)

Investigation – RSSI

RSSI

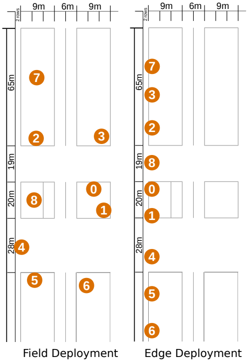
- Exemplary results of *Node 0* (Edge deployment)

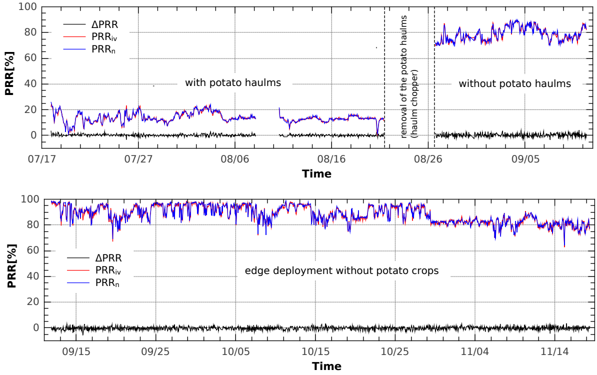


Overall result: No correlation between undervolting and the RSSI can bee seen ($r(\Delta RSSI, \nu)$)

Investigation – Packet Reception Rate

Exemplary PRR for *Node 0*



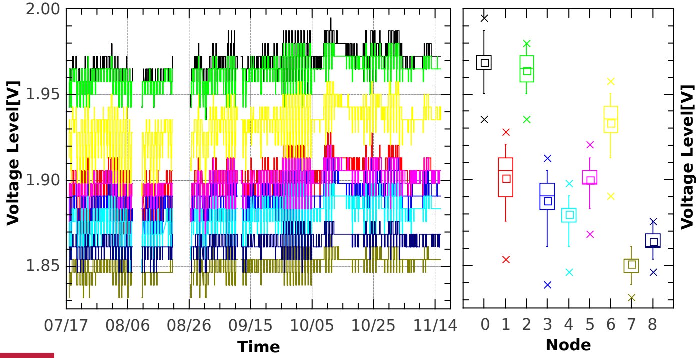


- **Overall result:** No correlation between undervolting and the PRR can bee seen $(r(\Delta PRR, \nu))$.

IdealVolting characteristics

Nominal voltage level (2.4V) is significantly undercut

- Heterogeneity in terms of minimum voltage capability
- No ALU errors were detected ($\approx 10^7$ spot-tests per node)

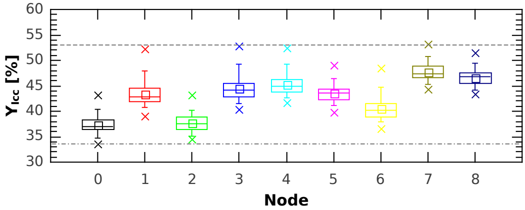


Energy savings

Emulation of the current consumption

- Calculation of savings in current consumption $Y_{I_{cc}}$ for each node
- Previous model of $I_{cc}(\nu, T) = p + s \cdot T + t \cdot \nu$

with $p = -4.558[mA]$, $s = -11.976[\mu AK^{-1}]$ and $t = 3.770[mAV^{-1}]$



Kulau et.al., *Paint it Black: Increase WSN Energy Efficiency with the Right Housing*, ACM RealWSN '15, 2015

Conclusion

Considering undervolting in WSNs:

- Rethink the constraint of absolute reliability and save energy

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  - Deployed on a trial field for potato crops
  - Allows convenient WSN experiments like on your desk
- Long-term
  - Virtually compare undervolted/normal powerd WSN
  - Real world measurements ($\approx$ 4 months)

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Results:

- Undervolting has **no negative impact** on the characteristics of a WSN
  ... but increases energy efficiency significantly

Thank you for your attention! Questions?

Ulf Kulau

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