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

Ulf Kulau, Stephan Rottmann, Sebastian Schildt, Johannes van Balen and Lars Wolf
Institute of Operating Systems and Computer Networks
TU Braunschweig
Email: [kulau|rottmann|schildt|vanbalen|wolf]@ibr.cs.tu-bs.de

***Abstract*—The fault-tolerant character of WSN protocols and applications that do not assume completely reliable systems legitimize undervolting – a highly efficient energy management technique where the supply voltage is set below the minimum specifications. As has been shown in earlier work, by using the reliable IdealVolting undervolting scheme the lifetime of WSN applications can be increased significantly while keeping the node in a safe state even under rough environmental conditions. To show the usability of undervolting in a real world WSN deployment, we performed a long-term study of IdealVolting in a Smart Farming application. All measurements were performed on a generic outdoor testbed for WSNs (PotatoNet) which is also presented within this paper. We collected a long-term dataset of a WSN running for one farming season on a potato field to compare the reliability and performance characteristics of IdealVolting against a regular powered WSN.**

I. Introduction

The limping evolution of batteries on the one hand and the growing field of challenging Wireless Sensor Network (WSN) applications on the other necessitate advanced power-management techniques on several layers. Existing solutions for energy management act conservatively, including reserves and safety margins, neglecting the fact that a WSN on the lower layers is not a reliable system: For example, connectivity can be fluctuating and unpredictable, and nodes may fail any time due to energy problems or hardware failures due to rough environmental conditions. Instead reliability is realized by upper layers such as specific network protocols and careful application design.

Hence, it is time to rethink the constraint of absolute reliability when aiming to increase the energy efficiency significantly. Operating WSN nodes at voltage levels below their minimum recommendations, offers such a potential of significant energy savings but at an increased risk of failures [1]. In [2] we proposed IdealVolting, which is an adaptive and reliable undervolting scheme for WSN nodes. IdealVolting tries to combine aggressive energy savings with reliability by finding safe operating areas below the minimum specification for each individual node under different temperatures. IdealVolting uses a supervised learning strategy which is able to keep the nodes in safe states even if the environmental conditions are constantly and rapidly changing.

In this paper we focus on a real world application and perform a long-term study of about 4 months to examine the performance of IdealVolting in WSNs. While [2] has demonstrated the energy saving potential of IdealVolting, in this paper we wanted to measure by how much, if any, IdealVolting decreases baseline reliability of a real WSN.

For this purpose we firstly present PotatoNet – a robust outdoor WSN testbed for Smart Farming applications. The PotatoNet testbed was used to evaluate the WSN reliability by continuously alternating between IdealVolting and operating at a nominal voltage level.

In consequence we are able to compare an undervolted WSN using IdealVolting against a normally powered WSN. As far as we know this is the first work that evaluates undervolting within WSN in a real world deployment. We will show that there is a difference between individual nodes regarding their undervolting capability and that IdealVolting can adapt to these individual differences. The measurements show that IdealVolting fulfills the promise of increasing energy efficiency significantly without having a measurable negative effect on WSN reliability.

II. IdealVolting

An important aspect to be considered when undervolting the micro controller units (MCUs) of a sensor node is that the voltage ratings given in the datasheet cover a large temperature range. Yet, the threshold voltage (V_{th}) of a Complementary Metal-Oxide Semiconductor (CMOS) gate is temperature dependent. For the threshold voltage V_{th} at temperature T the following equation holds

$$V_{th}(T) = V_{th0} + \alpha \cdot (T - T_0) \quad (1)$$

where V_{th0} is the threshold voltage at the temperature T_0 and α is a temperature coefficient [3]. While MCU manufacturers need to specify their minimum voltage for worst-case conditions at the extreme of the allowed temperature range and taking production variances into account, Equation (1) implies that under most conditions an MCU has the ability to run well below its specified minimum voltage.

The actual voltage level at which a node or an MCU still works properly depends on the clock speed, the temperature, and its individual properties due to variations in the manufacturing process. To adapt each node to its "ideal" voltage level, IdealVolting implements a control loop between an undervolted main MCU and a tiny but reliable co-MCU. While the main MCU executes a spot-test periodically, the co-MCU validates the test-results to decide whether the voltage level can be lowered or not. By collecting a set of absolute minimum voltage levels where malfunctions are detected, the co-MCU

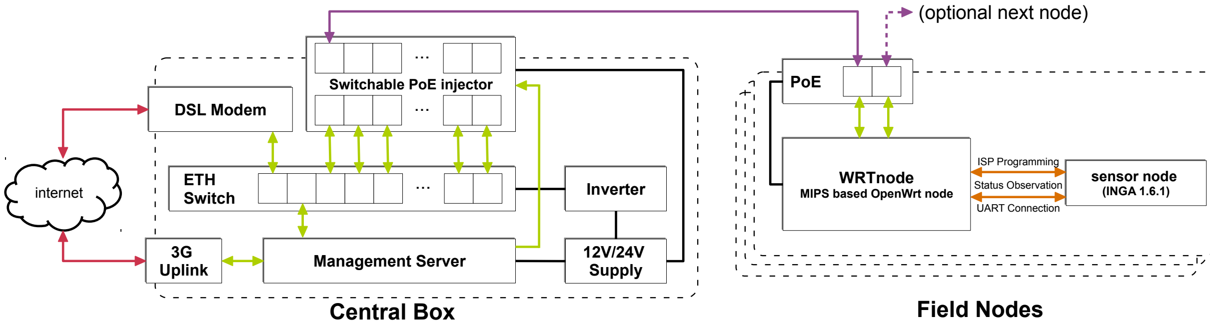


Figure 1: PotatoNet system architecture.

facilitates a supervised learning process. It is able to learn and predict a safe voltage level for a given temperature value $V(T)$ on a node-individual basis.

Of course, the additional hardware incurs some overhead that needs to be offset by the gains of undervolting. In our earlier work we have already shown, that this is possible and the lifetime of WSN applications can be increased significantly [2]. In this paper the scope is to determine whether adaptive undervolting has an impact on the reliability of WSN applications.

IdealVolting mainly affects the MCU of the sensor node (ATmega1284p). In this context it is important to mention that although the transceiver is connected to the same voltage path as the undervolted MCU, during our evaluation the specified minimum voltage level of the transceiver ($V_{rf} = 1.8\,\text{V}$) was never undershot. Hence, the transceiver unit of the nodes has never been undervolted during this experiment.

III. PotatoNet – Outdoor WSN Testbed

In this work the goal is to determine the stability of adaptively undervolted WSN nodes under realistically changing environmental conditions. These conditions can be encountered in Smart Farming applications. Smart Farming is an upcoming application area for WSNs, which are used to analyze and monitor the conditions of the soil and crops in order to optimize yield and minimize the use of fertilizer and pesticides. Hence, to evaluate IdealVolting against the backdrop of a real world application, we entered a cooperation with a potato research station[1] in Northern Germany, that allowed us to use one of their trial fields for our outdoor WSN testbed – PotatoNet.

Although the basic intention of PotatoNet was to evaluate undervolting in WSNs, the testbed was designed to be generic for further research. As the testbed is around 100 km away from the university and is intended for long-term experimentation, the overall system design strongly focuses on robustness.

This section gives an overview on the PotatoNet's architecture and the challenges that are typically encountered when setting up a WSN testbed outdoors.

The PotatoNet architecture depicted in Figure 1 consists of a "Central Box" that manages the communication uplink, data collection and power distribution and a number of "Field Nodes" that contain a WSN node and supporting hardware.

[1] http://www.vsd-dethlingen.de

A. Power Supply and Distribution

Due to the need for a management server, the programming hardware and a potentially large amount of nodes, it is clear that the whole PotatoNet setup cannot be run off a couple of batteries. However, since for certain remote scenarios operating from a battery-buffered off-grid solar array might be the only option, the whole electronics of the central box is designed to be able to run off a 24 V DC supply. The central switch is the only component that requires 230 V AC, therefore an AC inverter is used to power it. At our test field mains power is available, therefore the central box includes a 300 W 24 V DC power supply for itself and all field nodes.

Power is distributed to the field nodes using Passive Power over Ethernet (PoE), which uses some lines in an Ethernet cable for DC power without any signaling. This reduces the maximum Ethernet speed to 100 Mbps, which is not a problem for PotatoNet's use case. The PoE injectors can be switched on and off individually by the management server. This allows a hard reset of nodes that are stuck and it can be used to power off nodes that are not part of a running experiment.

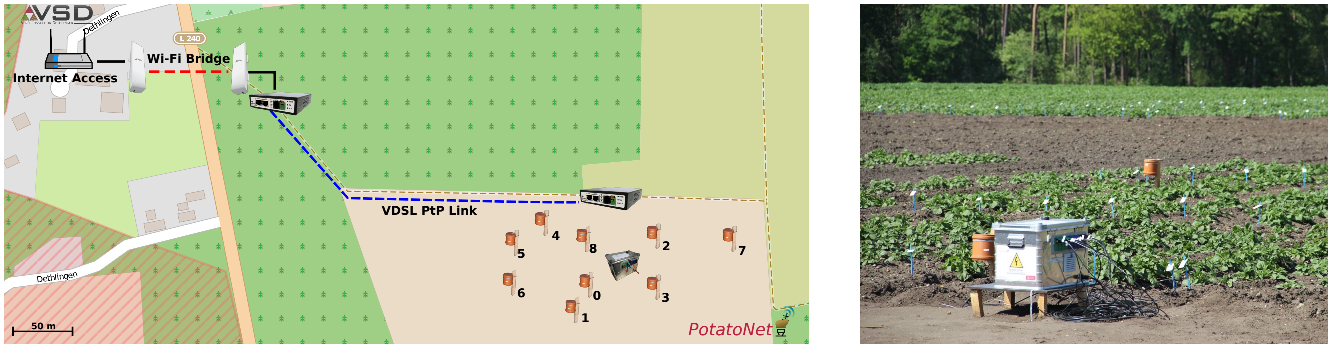
Upon reboot all PoE injector ports are disabled and will not be enabled automatically. This is a safety feature in case one of the nodes develops a short circuit, triggering a crash of the rest of the system. By restarting without any active node, such problems can be debugged remotely by activating the nodes one by one.

The power usage of the whole system is around 45 W for the central box with 2 W added for each field node.

B. Central Box

The central box of PotatoNet is mainly based on an embedded PC – called "Management Server".

Management Server: The management server is an IPC (Advantech ARK-1360F-S6A1E) running Debian Linux. It has no moving parts as it is fan-less and boots from a Compact Flash card. We integrated a cellular data card so the management server has a network connection, even if the rest of the PotatoNet network breaks down. We choose fairly robust hardware for the management server, as it is a crucial component. While it is not a problem if some remote



(a) Node locations and uplink components

(b) Field view – Central box and field nodes.

Figure 2: PotatoNet deployment at trial field of the VSD research station in Dethlingen.

nodes fail, without the management server it is not possible to interact with the testbed remotely. As long as electricity supply is available, the management server should boot up and build a network connection.

Central Box Mechanics: All components of the central box are mounted inside a 73 liter aluminum box (60 x 40 x 41 cm^3, see Figure 2b). We use rugged connectors for Ethernet and power to protect against dust and humidity. For thermal reasons a filter fan with 15 $\mathrm{m}^3\,\mathrm{h}^{-1}$ throughput and an additional filtered air intake on the opposite side provide some airflow through the case. This kept the air temperature under 40 °C even under direct sunlight during the summer season.

C. Field Node

The PotatoNet design includes an independent system that communicates with the management server and is able to program and collect data from a WSN node.

Programming Platform: We decided to go for an embedded Linux platform for cost and flexibility reasons. Every WSN node is paired with a WRTnode[2]. The WRTnode includes a 680 MHz MIPS (MT7620 [4]) processor and 64 MiB of RAM. It runs the OpenWRT[3] embedded Linux distribution. The WRTnode supports a number of GPIOs, which can be used for In System Programmer (ISP) programming of the WSN node. Two Ethernet MACs are supported which allows communication with the management server as well as chaining WRTnodes. As an added bonus the WRTnode includes a complete Wi-Fi implementation, which means the PotatoNet can also be used for Wi-Fi experiments. A single WRTnode costs USD 25, which is cheaper than having a low production run of less powerful, custom designed hardware. By supporting OpenWRT a large amount of standard Linux software is available for installation directly from the OpenWRT repositories. This makes programming or processing data collected from the WSN node easy.

To interface the WRTnode with the WSN node and connect it to the management server we designed a simple companion board which includes some passive components for the ISP programmer and two Ethernet jacks and a DC-DC voltage regulator that can generate the required 5 V DC supply from the PoE supply. The WRTnode and the INGA WSN node can be plugged into the companion board directly. Including components, the board adds about USD 10 to the price of a node.

WSN Node: We use the INGA WSN node [5] in version 1.6.1. This version of the node is a derivation of our first undervolting capable sensor node presented in [2]. The design includes an IEEE 802.15.4 transceiver (AT86RF233) as well as two microcontrollers (ATmega1284p, ATtiny84) to enable the IdealVolting implementation. However, for more details about the node's architecture we would like to refer to [2].

The WRTnode is able to program both INGA processors independently by using standard programming software[4].

Node enclosure: We needed an enclosure to hold the INGA node and WRTNode. In contrast to the central box, we went for a cheap design without costly rugged connectors. Of course, weather ruggedness should not be compromised. We ended up with a design based on standard PVC-U tubing with 160 mm diameter. We used a drainage double socket closed with two socket plugs. The electronic components have been mounted to one socket plug. As only one (or two for cascading) Ethernet cable needs to go into enclosure we used simple cable glands. The total cost for one enclosure is about USD 10. Figure 2b shows two deployed enclosures (in orange) on the potato field.

D. Network Architecture

In the PotatoNet system there are several physical and logical networks running in parallel. The Ethernet networks are separated by VLANs and managed by the switch in the central box. Only the management server has access to all VLANs. The following networks exist in PotatoNet:

IEEE 802.15.4 network: Network between the INGA WSN nodes (cf. Section III-C). This network is used for the actual long-term evaluation described in this paper. It is neither required for logging nor for reprogramming. Hence, the evaluation is not influenced by any overhead due to maintenance messages.

[2] http://wrtnode.com/

[3] https://openwrt.org

[4] http://www.nongnu.org/avrdude/

WRTnode Ethernet network: One Ethernet port of each WRTnode is connected to the central box. The management server can connect to the WRTnodes and execute actions such as reprogramming the attached INGA node or collecting logged data. If the main uplink is available, the WRTnodes can access the Internet which simplifies updating or installing new software. If the PotatoNet falls back to its (metered) backup uplink, Internet access for the WRTnodes is cut, but they can still connect with the management server. Because we equipped each WRTnode with two Ethernet ports in a switch configuration, WRTnodes can be daisy-chained. Due to the low power draw and the comparatively high PoE voltage of 24 V this is efficient enough to daisy-chain several field nodes.

Main uplink: One Ethernet port of the central box is reserved for the Internet uplink. It is just expected that an IP address with Internet access can be obtained via DHCP autoconfiguration. Therefore, it is enough to connect the uplink port to a typical SOHO router. If needed, the uplink port can be permanently powered, for connecting PoE equipment such as a Wi-Fi bridge.

Cellular backup uplink: When the main uplink fails, a cellular backup, driven by a UMTS card in the management server will be used. Even when most components fail, as long as the management server gets electricity and boots up, a researcher can login through the cellular backup and analyze any problems.

Device management network: The manageable switch as well as components such as Wi-Fi bridges usually contain some web-interface for configuration. We put the management interfaces of these devices into a separate VLAN that can be reached via the management server. This allows monitoring and reconfiguration of these devices even after PotatoNet is deployed.

E. Deployment

Before deploying the testbed at its final location, the central box and field nodes have been tested by running on an exposed spot on the roof of a university building for 4 weeks. This enabled us to test resistance to various weather conditions and assess the general reliability of the system, while still being able to access it easily. We could verify that the enclosures can withstand heavy rain and that direct exposure to the sun is not a problem from a thermal point of view. Afterwards, we deployed 9 field nodes and the central box on a farmed testing field from the VSD research station for potato crops to perform our long-term evaluation.

As the installation is 100 km away from the university and cellular connection is too unreliable to act as the sole uplink, we needed a secondary (stable) internet connection. The next low-speed DSL landline is around 450 m away inside the research station. Due to a street and a small forest in between the station and the field, a direct Wi-Fi link is infeasible. We opted to cross the street with a Wi-Fi Bridge and use a VDSL point-to-point link to bridge the distance to the field. Figure 2a depicts the deployment, the location of field nodes and the main uplink topology.

IV. Long-term Evaluation

The intention of the long-term evaluation is to show the usability and reliability of an undervolted WSN compared to a WSN where all nodes run at specified voltage levels.

Therefore, we let all field nodes change periodically between IdealVolting and using nominal voltage according to the datasheet. By switching modes every 144 seconds, we can ensure that nodes experience similar environmental conditions whether using IdealVolting mode or running with nominal voltage.

Every INGA WSN node executes a process which is able to handle commands via Universal Asynchronous Receiver/Transmitter (UART). These commands are sent by the central box via the WRTnode connected to an INGA. There are commands to force the node to (i) enable/disable the IdealVolting process and (ii) to send data to a given *destination* at a given *tx-level* with a given *payload*.

As the WRTnode is connected to the node's UART, a virtual connection to the management server can be used to delegate the entire evaluation by the central box. For the evaluation we used 9 field nodes. Every node is able to send the data at 16 different tx-levels ($[0 = +4\,\text{dBm}, ..., 15 = -17\,\text{dBm}]$) [6]. The payload message includes a unique and consecutive sequence number n and the current temperature T at the sender itself, which is a very typical task for a WSN application.

All debug outputs of the nodes were collected by the central box via the virtual UART connection. Algorithm 1 depicts the pseudo-code running on the management server orchestrating the experiment.

Algorithm 1 Centralized scheduler

```
iv ← on
while true do
    for each node i ∈ N do
        tell node i set IdealVolting=iv
    end for
    for each node i ∈ N do
        for each tx-level l ∈ S do
            tell node i to broadcasts (i, l, T, n)
            n ← n+1
            wait 1s
        end for
    end for
    if iv == on then
        iv ← off
    else
        iv ← on
    end if
end while
```

The central server will ask each WSN node in turn to send a packet at a given transmit power while executing either IdealVolting or not. The sent data includes the node's address i, the tx power level l, the sensed temperature T and a sequence number n uniquely identifying the transmission. The destination of each message was the broadcast address of the WSN. Every node within the communication range of the respective sender logs the received information (i, l, T, n) and adds information about the received signal strength indicator (RSSI) and local temperature T_l. This data is sent via UART and the WRTnode network to the management server.

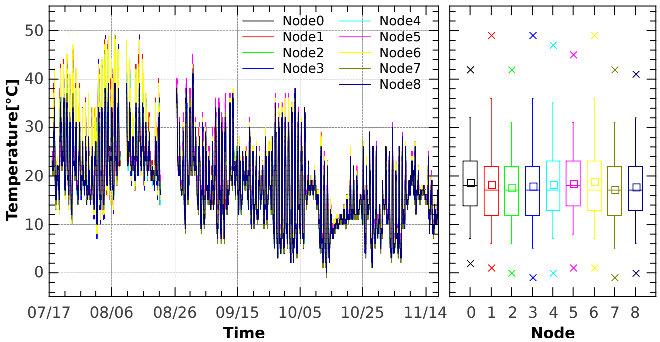


Figure 3: Temperature values of all nodes.

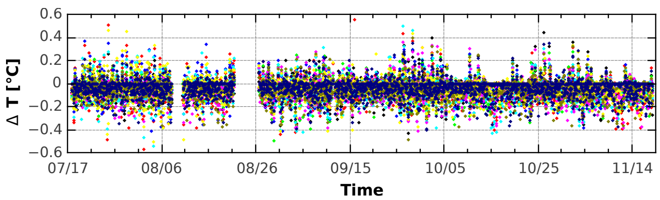


Figure 4: Differences of temperature measurements between undervolted and normal powered nodes ΔT.

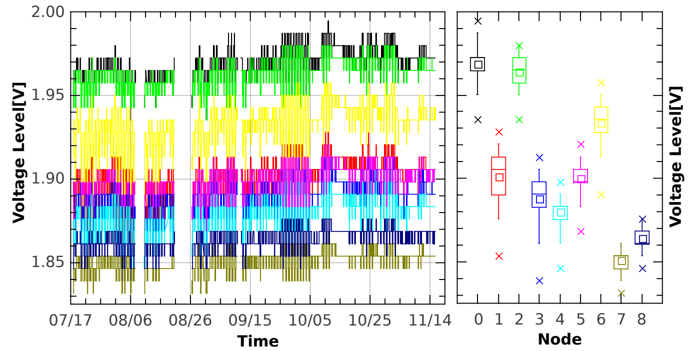


Figure 5: Voltage levels of all nodes during IdealVolting. Significant heterogeneity in terms of minimum voltage capability of individual nodes can be observed.

Before the start of this study, each node has already learned its individual undervolting characteristic $V(T)$ [2]. This model will only be adapted by IdealVolting, if errors occur.

In total we collected 7.5 GB of data over a time span of almost 4 months. Three different scenarios can be considered, as the potato crops had been farmed and harvested during our study.

- At the beginning the potato crops grew and the links between nodes were influenced by the water-rich plants (07/17 – 08/21).
- In the second phase the plants were chopped so that no plants shadowed the communication between nodes (08/25 – 09/11).
- For the last stage all nodes were moved and deployed at the edge of the field, to avoid the destruction of the testbed as the potatoes were harvested (09/11 – 11/18).

A. *Temperature Measurement*

The simplistic Smart Farming task performed by each WSN node was to sample the surrounding temperature with 1 Hz sample rate, and to store the data on the WRTNode. This ensures that nodes are busy processing data even while they are not currently asked by the central scheduler (cf. Algorithm 1) to transmit a temperature update. Thus, we have a higher chance of provoking errors during the IdealVolting phase.

Figure 3 shows the measured temperature values of all nodes for the entire duration of this study. Beside the maximum values of $-1\,°C \leq T \leq 49\,°C$ the high fluctuation of T indicate that WSNs deployed on a field are exposed to a challenging environment. Although all nodes sampled almost the same environment, there are slight variations between the nodes which is also depicted in Figure 3. This is due to the differently sized potato crops. While some nodes were covered by leafs, others experienced more exposure to direct sunlight.

B. *IdealVolting Characteristics*

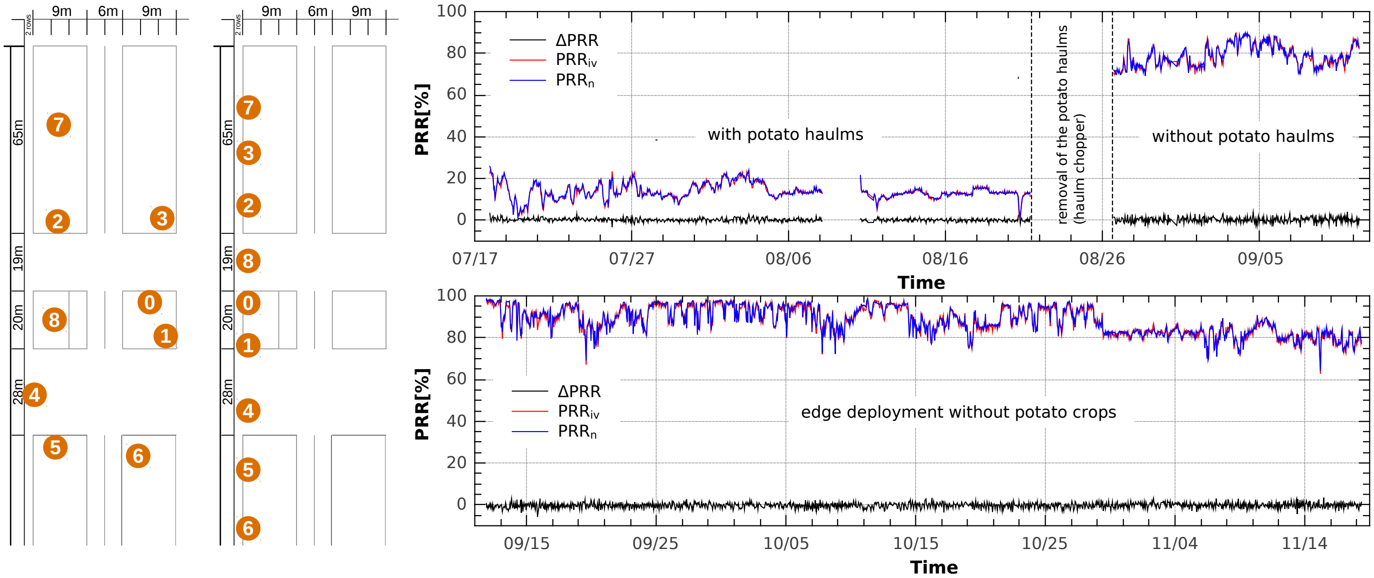
During this study each node operated at a fixed clock rate $f_{cpu} = 8\,\text{MHz}$. For this frequency the manufacturer specifies a safe operating voltage of at least 2.4 V [7].

The ideal voltage level (absolute minimum voltage level without malfunction) chosen by IdealVolting depends on (i) the individual characteristics of the MCU and (ii) on the temperature experienced by the node. The minimum voltage levels are inversely proportional to temperatures so that the IdealVolting process continuously adapts the voltage to operate the MCU with the lowest voltage that is still within the learned safe operating area. In Figure 5 the continuous adaptation of the nodes as well as the individual characteristics caused by different intensities of adaptation can be seen. As a consequence the strong temperature dependency of the absolute minimum voltage level and the individual characteristics of nodes add a strong heterogeneity to the network. This node-individual information might be used in the future to further optimize routing and load balancing approaches in WSNs to increase the lifespan of the whole network.

To check the correctness of results from an undervolted MCU, IdealVolting does a regular spot-test that is evaluated by the safe co-MCU (cf. Section II). This spot-test is based on the examinations of [8] which shows that a simple matrix-multiplication is sufficient to detect arithmetic logical unit (ALU) errors [9], [2]. For this evaluation the spot-test was also executed when the nodes were running with nominal voltage. All test-scores have been logged at the central box. In total each node executed $\approx 10^7$ spot-tests. During the whole study neither normal powered nodes, nor nodes running IdealVolting ever failed a spot-test.

C. *Impact on Sensing Quality*

As the temperature measurement was performed by both the WSN running in IdealVolting mode and the WSN running with normal voltage, we can answer the question whether undervolting influences the quality of sensed data. The correct operation of the MCU is only one aspect of a correctly



(a) Field-topology (b) Edge-topology (c) Node 0: PRR – field deployment (top figure) and PRR – edge deployment (bottom figure)

Figure 6: Topology of the field and edge deployment with exemplary results of the PRR for node 0.

Table II: Summary of the PRR evaluation and comparison. Table includes the mean values of the PRR for undervolted and normal state ($\overline{\text{PRR}_{iv}}$, $\overline{\text{PRR}_{n}}$), the mean value of the difference with standard deviation ($\overline{\Delta\text{PRR}}$) and the correlation $r(\Delta\text{PRR}, v)$.

	Field deployment (with potato haulms)				Field deployment (without potato haulms)				Edge deployment (without potato crops)			
Node	$\overline{\text{PRR}_n}$	$\overline{\text{PRR}_{iv}}$	$\overline{\Delta\text{PRR}}$	$r(\Delta\text{PRR}, v)$	$\overline{\text{PRR}_n}$	$\overline{\text{PRR}_{iv}}$	$\overline{\Delta\text{PRR}}$	$r(\Delta\text{PRR}, v)$	$\overline{\text{PRR}_n}$	$\overline{\text{PRR}_{iv}}$	$\overline{\Delta\text{PRR}}$	$r(\Delta\text{PRR}, v)$
0	13.64	13.84	0.199 ± 0.756	0.0220	78.59	78.91	0.316 ± 1.990	-0.0241	88.15	87.88	-0.271 ± 1.183	-0.0941
1	9.61	10.00	0.387 ± 0.797	-0.0501	78.72	79.33	0.609 ± 1.548	-0.3945	85.24	85.43	0.184 ± 1.251	-0.0413
2	5.05	5.18	0.129 ± 0.726	0.0083	54.29	54.67	0.384 ± 1.380	-0.1904	74.41	74.66	0.241 ± 1.257	-0.2247
3	17.64	17.69	0.051 ± 0.939	0.0560	82.39	82.17	-0.218 ± 1.052	-0.0949	78.58	78.29	-0.287 ± 1.162	-0.0387
4	20.47	21.50	1.025 ± 1.462	-0.3214	83.00	83.18	0.184 ± 1.264	-0.2864	88.11	88.31	0.201 ± 1.269	-0.0183
5	6.84	7.07	0.229 ± 0.605	-0.1595	68.08	68.55	0.463 ± 1.431	-0.3150	76.36	76.91	0.544 ± 1.383	0.0383
6	11.96	12.07	0.114 ± 0.775	-0.1161	59.56	60.53	0.971 ± 1.630	-0.3444	55.14	55.93	0.786 ± 1.366	-0.2974

Table I: Difference in measured temperature between IdealVolting and normal operation. No correlation $r(\Delta T, v)$ between temperature difference and voltage → IdealVolting is not influencing the sensed data.

Node	$\overline{\Delta T}[°C]$	$_{max}(\Delta T)[°C]$	$_{min}(\Delta T)[°C]$	$r(\Delta T, v)$
0	-0.0327 ± 0.0705	0.4433	-0.4317	-0.0324
1	-0.0450 ± 0.0849	0.5490	-0.5711	0.0134
2	-0.0346 ± 0.0697	0.2962	-0.4938	0.0045
3	-0.0339 ± 0.0757	0.3658	-0.4165	0.0029
4	-0.0418 ± 0.0832	0.4948	-0.5472	0.0340
5	-0.0401 ± 0.0741	0.3605	-0.4115	-0.0134
6	-0.0364 ± 0.0808	0.4604	-0.5026	-0.0073
7	-0.0420 ± 0.0753	0.3920	-0.4873	-0.0376
8	-0.0429 ± 0.0755	0.3499	-0.4045	-0.0056

operating node. If IdealVolting reduces the accuracy of sensed data, we need to know as this might not be acceptable for some applications.

For each node, Figure 4 depicts the difference between the temperature measurements in IdealVolting and normal powered state for all nodes ΔT. It can be seen that the absolute deviation is always $< \pm 0.6$ °C. To prove that the quality of sensing is not influenced by undervolting, we correlated the voltage level v of the nodes with the respective differences ΔT between the measurements performed in IdealVolting and normal mode. If there was a connection between measurement deviations and voltage levels, the correlation coefficient $r(\Delta T, v)$ would reveal this. The results are shown in Table I. For each node we calculated the average temperature difference $\overline{\Delta T}$ and standard deviation between IdealVolting and normal operation. The minimal and maximal measurement differences show that we do not have any outliers, where we get a temperature difference significantly above the average difference. Finally, the correlation coefficient $r(\Delta T, v)$ proves, that there is no correlation between voltage level v and the difference in temperature measurement ΔT.

Knowing this we can also infer that in both states, IdealVolting and normal operation, the WSN experienced the same environmental conditions. By switching between IdealVolting and normal mode every 144 s we really are comparing the two operating modes under the same environmental conditions.

D. Characteristics of PRR

Another major question is whether undervolting has an impact on the performance of the WSN communication. The Packet Reception Ratio (PRR) is the most important metric here. Any energy savings by the MCU would immediately be offset if a decreased PRR in IdealVolting mode demands costly packet retransmissions.

To analyze the connection between undervolting and the PRR of a WSN we first define the PRR as the percentage of packets that have been received out of all sent packets. Hence, we calculated the PRR of each node for all broadcasted messages from every *other* node at every tx-level. Due to the centralized logging we know

1) When a node transmitted a message.
2) Whether the WSN was operating in IdealVolting mode or not at this time.
3) What was the content of the message (i, l, T, n) (cf. Section IV).
4) Which other nodes received this message.

Therefore, we are able to consider the PRR in the IdealVolting mode (PRR$_{iv}$) and nominal voltage mode (PRR$_n$) separately.

Figure 6 shows the PRR of node 0 for the different scenarios described in Section III-E. Figure 6a shows the topology of the field deployment while the top figure of Figure 6c shows the corresponding PRR$_n$ and PRR$_{iv}$ over time. The difference between the PRRs is depicted as ΔPRR = PRR$_n$ − PRR$_{iv}$. The short interruption (08/08 - 08/10) results from a temporary usage of the PotatoNet for a different short-term experiment.

It is obvious that the potato crops have a significant impact on the PRR. After a haulm chopper removed the potato crop haulms on August 28th, the PRR immediately increased by ≈ 4 times. On September 11th we rearranged the nodes at the edge of the field due to the final harvesting of the potato crops. Figure 6b shows the changed topology. The bottom figure of Figure 6c plots the corresponding PRR values.

In all scenarios the PRR of node 0 stays almost equal for both WSN states. The difference ΔPRR seems negligible. This is a good indication that IdealVolting is not influencing the PRR. To prove this, similar to the argumentation in Section IV-C, we correlated the voltage level during IdealVolting v with the difference in PRR, ΔPRR. If undervolting impacts the PRR of the WSN the correlation coefficient $r(v, \Delta\text{PRR})$ would show a statistical relationship.

Table II summarizes the entire evaluation including the correlation $r(\Delta\text{PRR}, v)$ in every scenario for the nodes 0 to 6. Nodes 7 and 8 have not been considered for this evaluation. Although both nodes operated throughout the entire evaluation, they received far fewer messages (around 1% of the amount the other nodes received). There is just not enough data for any meaningful statistical analysis. The weak reception rate of these nodes was independent of the voltage state. While there seems to be a bias toward negative correlation values, the absolute values are very low so that a statistical connection between undervolting and the PRR of the WSN can not be attested.

This analysis proves that IdealVolting has no negative effect on the performance of the wireless links.

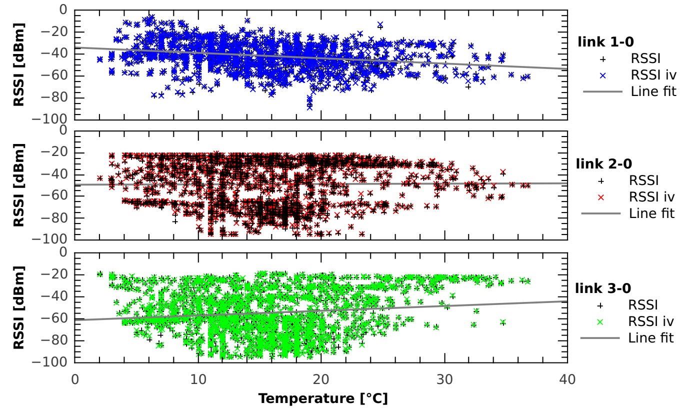


Figure 7: RSSI of undervolted and normal powered nodes against temperature (exemplary links).

E. Impact on RSSI

As already mentioned, the transceiver unit of the nodes is supplied by the same voltage path as the MCU. Hence, during IdealVolting the voltage level of the transceiver varies too. However, IdealVolting never falls below the minimum recommended voltage level of the transceiver (1.8 V).

To analyze whether the adaptation of the voltage level has an impact on the RSSI, we reused the method of correlating the voltage level v with the difference between RSSI of undervolted and normal powered nodes ($\Delta RSSI$). Table III shows the mean $\overline{\Delta RSSI}$ and standard deviation for links to node 0. As to be expected from the PRR results, the correlation coefficient $r(\Delta RSSI, v))$ indicates no connection between undervolting and the RSSI.

Recent publications stated that temperatures can influence the performance of wireless communication. Commonly used IEEE 802.15.4 transceivers suffer from high temperatures, as their internal amplifiers efficiency decreases [10], [11]. In [12] this effect is also validated. However, so far only one specific transceiver unit (TI CC2420 [13]) has been examined. As we have shown that undervolting has no impact on RSSI, we can take a look if and how temperature influences the performance of our 802.15.4 receiver. Different from previous work, the INGA node uses an AT86RF233 [6] transceiver.

Figure 7 shows the RSSI as a function of the temperature for three exemplary links. For this evaluation we only considered the edge topology, as this deployment was not affected by external events (e.g. plants). We can neither prove nor refute that higher temperatures tend to lower RSSI but a detailed

Table III: IdealVolting has no impact on the RSSI.

Link	$\overline{\Delta RSSI}[dBm]$	$r(\Delta RSSI, v)$
$1 \rightarrow 0$	0.11509 ± 1.01578	0.05137
$2 \rightarrow 0$	0.06573 ± 0.77007	0.02772
$3 \rightarrow 0$	0.05139 ± 0.91692	0.00508
$4 \rightarrow 0$	0.05924 ± 1.01099	0.01831
$5 \rightarrow 0$	0.00975 ± 0.80512	0.00694
$6 \rightarrow 0$	0.01332 ± 0.40945	-0.02496

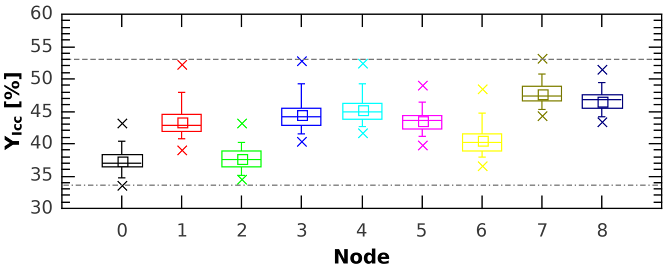


Figure 8: Savings Y_{Icc} of current consumption I_{cc} when using IdealVolting instead of normal supply voltage. High variations due to temperature and individual characteristics.

examination is beyond the scope of this paper.

F. Energy Efficiency of the MCU

Our results have shown that undervolting using IdealVolting neither impacts reliability nor sensing accuracy of the WSN application. However, IdealVolting has a significant impact on the energy efficiency of the nodes. In [14] we presented an energy model $I_{cc}(v,T)$ of the used MCU which was derived by measurements in a climatic chamber. Using this model, the current consumption of the MCU can be expressed by the following Equation:

$$\forall \begin{cases} 1.6\,\mathrm{V} \leq v \leq 2.4\,\mathrm{V} \\ -15\,^{\circ}\mathrm{C} \leq T \leq 60\,^{\circ}\mathrm{C} \end{cases} : I_{cc}(v,T) = p + s \cdot T + t \cdot v \quad (2)$$

with $p = -4.558\,\mathrm{mA}$, $s = -11.976\,\mu\mathrm{A\,K^{-1}}$ and $t = 3.77\,\mathrm{mA\,V^{-1}}$

With this model, it is possible to calculate the current consumption of the MCU for each node and every state and thus quantify the savings in current consumption Y_{Icc} due to undervolting.

For the sake of fairness we only compare the current consumption I_{cc} instead of the power dissipation. The power dissipation P would include the voltage level v which leads to even more savings due to IdealVolting as the voltage level is dynamically lowered depending on the temperature. However, when comparing the power dissipation the efficiency of voltage conversion plays a significant role. As this efficiency depends on the actual components (e.g., buck converter, linear dropout converter (LDO)) we limit our comparison to I_{cc}.

Figure 8 shows the distribution of current consumption savings across all nodes. Due to the experienced temperature and individual characteristics of each nodes the savings vary over time for each node. In total, the savings lay between 33.52% and 53.16%. This increase in the MCU's efficiency immediately translates into an increased lifetime for a WSN and knowledge about the individual characteristics of each node can be used to fine-tune, e.g., load balancing.

V. Conclusions

Violating the specified minimum voltage levels of components by undervolting increases the energy efficiency significantly. As operating MCUs outside their specification increases the risk of malfunctions, undervolting needs to be managed carefully. In previous work we presented IdealVolting, an adaptive self-learning undervolting scheme for WSN nodes that aims to preserve reliability while saving energy by undervolting.

In this paper we performed a long-term study to examine whether undervolting can be used for real-world WSN applications. For this purpose we presented PotatoNet – a robust outdoor WSN testbed – to run evaluations in a realistic Smart Farming scenario.

Our evaluation has proven that IdealVolting has no impact on the reliability of the wireless links and no impact on the quality of sensed data. Thus, the service quality the application running on the network is experiencing does not decrease when using IdealVolting. At the same time, IdealVolting saved up to 53% of MCU supply current, which directly benefits the network by increasing the lifetime of its nodes. Finally we also release all collected data for the community[5].

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