Paint it Black – Increase WSN Energy Efficiency with the Right Housing

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ABSTRACT

It is a well-known fact that Wireless Sensor Networks (WSNs) that are exposed to real environmental conditions suffer from harsh temperatures. Yet, the temperature does not only have negative impact as the energy efficiency of processing units benefits from higher temperatures. The minimal voltage for correct operation of CMOS circuits is bounded by the temperature. Thus, temperature-dependent undervolting schemes for WSN nodes have been proposed in the past to extend the network lifetime. However, not much thought has been given into directly influencing the most relevant factor: Temperature. In this work we look at the influence of various WSN housings onto the temperature profile of WSN nodes and quantify the energy saving potential of choosing the right housing.

1. INTRODUCTION

In the past the WSN community gained a lot of experience with the challenges of using WSNs for outdoor applications e.g. [1, 7]. One aspect is that nodes often are exposed to rough environmental conditions, particularly temperatures [11, 2]. Unfortunately, the nodes suffer from such extreme temperatures as the efficiency of IEEE 802.15.4 transceivers decreases with growing temperatures and thus, the reliability of transmissions decreases [9, 3]. However, an increased temperature does not only have negative effects on the operation of a WSN as the temperature has a significant impact on the energy efficiency of the sensor node.

Safe operating voltage for Complementary Metal-Oxide Semiconductor (CMOS) circuits depends on the environment temperature: With higher temperatures, and thus higher electron mobility, the minimum threshold voltage of CMOS gates decreases [6]. This has led to approaches undervolting components below their specified minimum voltage in order to save energy for battery powered devices like wireless sensor nodes [5].

As a micro controller unit (MCU), which is commonly used on wireless sensor nodes, is specified to cover a wide temperature range, even under normal conditions (room temperatures) the nominal voltage level can be undershot significantly without any negative impact on reliability. The voltage level itself has a quadratic impact on the dynamic power consumption of CMOS parts [10], thus for normal environmental conditions energy savings up to 42% at the processing unit are possible. Therefore, the occurrence of higher temperatures will lead to even lower acceptable minimum voltage levels where an MCU can be operated reliably [5]. Hence, temperature becomes an influencing factor for energy consumption and influencing a nodes temperature is one way to increase energy efficiency. Obviously, actively heating a node is not sustainable, however housings of different materials with different heat capacities and thermal conductivities can change the temperature a device experiences.

In this paper we will first present an energy model and the undervolting capacities of the INGA WSN node, which have been determined by controlled experiments. We will then present logged temperature data over three months using different WSN housings. Together with the energy model this allows us to calculate the energy needed to operate INGA in each of the housings and locations to see if any of them offers an advantage over others. Finally we wrap up by pointing out limits of the presented approach and discuss how the findings in this paper can help to optimize the energy efficiency of a WSN application.

2. TEMPERATURE VS. ENERGY

The current consumption of node components such as the processing unit and the transceiver unit are temperature dependent due to physical effects, which is well documented in the corresponding datasheets. Considering undervolting the connection between temperature and energy efficiency can be strengthened even more. As mentioned above, in our previous work [5] we have shown that MCUs can be operated below their recommended voltage levels, as the threshold voltage of CMOS gates is temperature dependent. Thus, the absolute minimum voltage level of an MCU is given as a function of the surrounding temperature ($V_{uv}(T)$). We took $i = [0...14]$ undervolting-capable INGA [5, 4] sensor nodes and measured their absolute minimum voltage levels for reliable operation at different temperatures to determine $V_{uv_i}(T)$. In this case the nominal minimum voltage for the MCU on INGA is $2.4V$@8MHz. Due to imperfections and fluctuations in CMOS production the minimum acceptable voltage of individual chips differs, so that every sensor node has its own individual characteristic curve.

RealWSN '15, November, 2015, South Korea

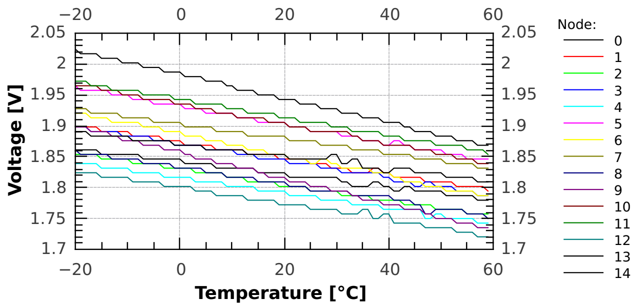

Figure 1: Characteristic curves of undervolted ATmega1284p MCUs on the INGA sensor node.

Figure 1 shows the result of this evaluation. All nodes are able to operate significantly below their recommended voltage level. Moreover, higher temperatures allow nodes to run at lower voltage levels. To get a comprehensive energy model for the INGA node we measured the current consumption of sensor nodes with changing voltage levels at different temperatures in a climatic chamber. For this evaluation the consumption of a whole sensor node with all components is considered while the transceiver unit was set to sleep state, so that the main current consumption depends on the MCU only. The considered temperature range reaches from $-15°C \leq T \leq 60°C$. Figure 2 shows the result of this measurement. When considering both, voltage and current consumption. Overall, higher temperatures leads to increased energy efficiency.

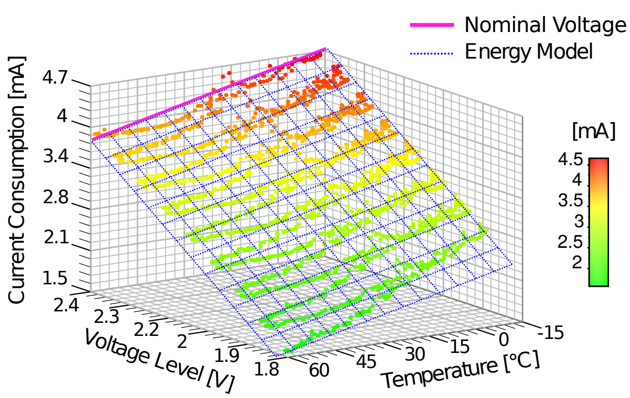

Figure 2: Measurement of the current consumption of the INGA wireless senor node at different voltage levels and temperatures (transceiver unit in sleep mode)

Based on these results we derived an energy model by using regression calculation. With an average deviation of 1.97% from the measured values, the model of the current consumption as a function of the temperature T and the voltage level v can be given as follows:

$$\forall \begin{cases} 1.6V \leq v \leq 2.4V \\ -15°C \leq T \leq 60°C \end{cases} : I_{cc}(v, T) = p + s \cdot T + t \cdot v \qquad (1)$$

with $p = -4.558872[mA]$, $s = -11.97692[\mu AK^{-1}]$ and $t = 3.770542[mAV^{-1}]$.

Combined with the individual characteristics of each node as shown in Figure 1, which can be represented by a linear approximation of the form $V_{uv_i}(T) = a_i + b_i \cdot T$, the power consumption of an undervolted sensor node can be calculated as a function of the temperature only.

(a) Direct sunlight (b) Shadowed location

Figure 3: Experimental Setup

3. EXPERIMENT

To quantify the potential energy savings from optimal temperature profiles we performed a long term measurement of the temperatures experienced by sensor nodes in 4 different housings and 2 different locations. As a baseline we measured the air temperature, which an unpackaged sensor node would experience during its probably short life. In addition to that we measured the temperature inside the normal INGA case, which is an ABS printed plastic enclosure. Further, a transparent glass enclosure has been used, to determine whether the expected green-house effect will have a positive impact. Finally, one housing was a stone normally used in storage heaters. The idea is that the large thermal capacity of the stone might be helpful by sustaining high temperatures for a longer time. Each housing as well as the air temperature has been measured under direct sunlight as well as in the shadow.

The measurement setup can be seen in Figure 3. We ran the measurements for approximately 3 months from May to July in Northern Germany. Every 10 seconds we took a temperature sample for each housing. Current measurement status and the opportunity of requesting temperature traces are available for the community[1].

3.1 Results

With the measured temperature charts for each day, the energy model from Equation 1 and the undervolting characteristic of a node as shown in Figure 1 it is possible to calculate how much energy a node consumes at a given location in a given housing. For the sake of simplicity for the following analysis we used a generic node characteristic which has been calculated as average from the 15 nodes examined in Figure 1.

Figure 4 shows the measured temperature. The detail plot on the right shows the temperature data from June 4th to June 7th. It is easy to see the daily pattern. During night, after everything cools down, there is virtually no difference between the different housing types. During day time the standard case and the glass reach the highest temperatures and thus seem to offer the best undervolting potential. It can be seen that the stone dampens temperature changes due to its higher heat capacity, but it does not seem to be able to hold the temperature significantly longer than the other housings. Table 1 concludes the measurement and

[1] `www.ibr.cs.tu-bs.de/users/kulau/PotatoNet-heat.html`

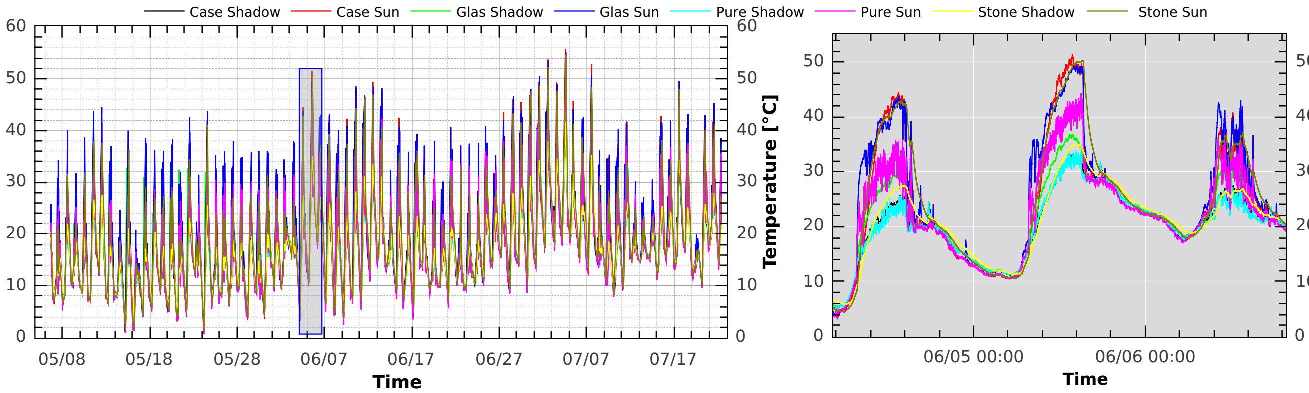

Figure 4: Longterm temperature measurement of different housings and locations.

			Case ●	Case ☼	Glas ●	Glas ☼	Pure ●	Pure ☼	Stone ●	Stone ☼
Absolut	Day	$\overline{T}[°C]$	17.663	20.719	18.949	21.803	17.231	19.116	17.915	21.280
		$\sigma_T[°C]$	4.388	5.629	4.436	5.480	4.460	5.072	4.518	5.733
	Night	$\overline{T}[°C]$	12.397	11.533	12.512	11.683	12.277	11.650	13.085	12.447
		$\sigma_T[°C]$	3.871	3.917	3.871	3.925	3.871	3.908	3.852	4.056
Percent	Day	$\overline{\Delta T}[\%]$	2.745	20.077	10.696	27.083	0.000	10.828	4.131	23.464
		$\sigma_{\Delta T}[\%]$	1.359	8.428	5.888	10.648	0.000	4.943	2.211	10.093
	Night	$\overline{\Delta T}[\%]$	1.097	-6.889	2.115	-5.557	0.000	-5.799	7.514	1.051
		$\sigma_D[°C]$	1.037	3.868	1.137	3.208	0.000	3.274	5.588	3.727

☼ - Sun
● - Shadow
σ_x - Std. Deviation
$\overline{x}$ - Mean
- Baseline

Table 1: Summary of the average temperature and the percent deviation from the baseline (Pure node deployed in shadow). During daytime the average temperatures of the housings differ a lot with the node in the glass showing the highest average temperature. During nighttime the differences between the housings is minor.

shows the averaged temperature with corresponding standard deviation of each housing for day- and night-time. For this evaluation the day-time is defined from dawn to dusk and recalculated for each day. Nevertheless, it should be mentioned, that the day-time does not equal the time of direct sunlight, as surrounding circumstances like trees and houses shadowed the experimental area well ahead of dusk. In addition Table 1 depicts the deviation of the temperature compared to the baseline, which is defined by the node that is deployed unpacked in the shadow (Pure Shadow).

We have chosen a very warm day (July 3rd) and a rather cold day (May 16th) within the measurement period and calculated how much energy a node would consume in each housing during day-time. The results can be seen in Table 2. In general it is clear that undervolting can achieve huge efficiency gains reducing energy consumption by a factor of up to 2.7. The data also clearly shows that higher temperatures are preferred, as they enable more aggressive undervolting, therefore energy efficiency is generally better in hot days. Due to the dependence between current consumption and temperature this is even true in the case when no undervolting is used. In any case a housing always improves things. On the hot day the stone housing with direct exposure to the sun gains another 4.0% energy efficiency compared to just putting the node in the shadow. For the cold day the glass exposed to the sun beats a shadowy place by 4.4%

To show the change of energy efficiency over a day Figure 5 outlines the percent gain of power dissipation compared to the baseline housing (Pure Shadow) for an exemplary day (July 17th). It can bee seen that the direct sunlight deployment leads to up to ≈ 8% more efficient processing just because of the right housing. All in all between the maximum reached temperature of $55.62°C$ (Case Sun) and the minimum temperature of $0.69°C$ (Pure Sun) the savings of power dissipation amounts to 40.5% when undervolting is applied.

4. DISCUSSION AND LIMITATIONS

We have seen that higher temperatures offer more undervolting potential and thus can improve energy efficiency. The evaluation focuses on processing unit energy consumption. When communication is considered the effects of temperature and potentially undervolting on the transceiver or used sensors need to be considered. As a rule of thumb undervolting a transceiver does not gain much, because it will always need to put a certain amount of energy in the air. However, the already mentioned negative impact on the transceiver's reliability at increased temperatures could lead to energy consuming retransmissions, which have to be taken into account.

There is also the question, whether higher temperatures will affect the aging of the electronic components significantly [8]. We assume with the tested housings, considering the process structures and tolerances of WSN node electronics this is not a problem, after all we did not reach higher temperatures than can be expected for a WSN node deployed outdoors, we just try to influence circumstances so those temperatures can be reached faster, more often and for a longer time. Of course, when trying to build special housings acting as a solar oven to further increase energy efficiency, this might become an issue.

It can be argued, that the differences between housings are

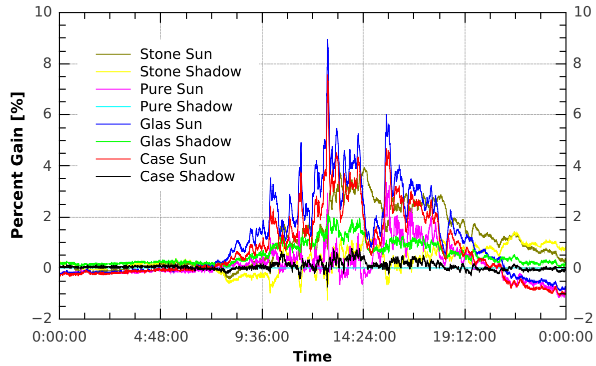

Figure 5: Gain in energy efficiency due to undervolting and housing effects compared to baseline (Pure Shadow) over the course of an exemplary day.

	Undervolted		Nominal Voltage	
	hot day	cold day	hot day	cold day
Case ●	323.76	376.83	852.46	902.86
Case ☼	313.07	374.58	843.63	901.05
Glas ●	320.99	374.26	850.17	900.90
Glas ☼	312.73	372.04	843.27	899.10
Pure ●	325.06	377.99	853.54	903.80
Pure ☼	318.94	376.02	848.44	902.32
Stone ●	322.68	377.95	851.67	903.87
Stone ☼	312.05	374.87	842.79	901.38

Table 2: Energy consumption of the nodes from dawn to dusk in $[J]$. For hot days the black stone case enables the highest energy savings.

not extraordinarily large, but keep in mind that you can get these optimizations for free: Just choose you sensor housing accordingly. At the very least just paint it black. Also, making sure your nodes are exposed to the sun, if possible, helps. This will also help in other ways: Your battery will be warmer too, which enables most battery technologies to deliver more capacity, thus the lifetime of a node should grow even more than suggested by the results presented in this paper. Vice versa, a damping housing, e.g. the Stone, could help to mitigate the adverse effects on the transceiver unit.

5. CONCLUSION

In this paper we firstly showed, that the temperature has a significant impact on the energy efficiency of wireless sensor nodes' processing units. When using undervolting this effect can be enhanced so that up to 40.5% more efficient processing was reached just because of the environmental temperature.

Hence, we evaluated different types of housing and deployment locations (direct sunlight and shadowed) to analyse the influence of their thermal characteristics. Together with a proposed energy model of a sensor node's processing unit, that also takes the temperature into account, we were able to determine the power dissipation under various environmental conditions.

A long term study was performed to show the benefit when choosing the right housing for an outdoor WSN deployment. We showed that the total amount of energy can be reduced and that there is a substantial variation over a single day. Nevertheless, we are also aware of the negative impact of high temperatures on the transceiver unit but at least we have a crux: High temperatures have a negative impact on the transceiver units but lead to a more energy efficient processing on the wireless sensor node.

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