Energy Saving Adjustments in a Wireless Sensor Network for Spatially and Temporally Highly Resolved Measurements of Environmental Parameters

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***Abstract*—Energy efficiency is essential for battery-powered long-life sensor networks. There is potential in several system levels for optimization targeting hardware and software. The required energy can roughly be estimated during operation based on data sheets and the expected operating time or measured with dedicated measurement tools. However, the software has a significant influence on the power consumption. The challenge is to evaluate the energy efficiency of a sensor node, especially after changes in software during development but also in its final operation. Small modifications can make a big difference here and reduce the battery life significantly. In this paper, an example for the optimization by software parameters is given, based on a real sensor network installation on a test field. Therefore a range test, using different antennas, data rates and transmission power was carried out and evaluated. The results where used to select transmission parameters in order to make the communication more reliable and reduce power consumption at the same time.**

I. Introduction

As part of the DAKIS project[1], a *Wireless Sensor Network (WSN)* was developed and installed. It was intended to operate over a period of at least 5 years, or if the project is extended for more than 10 years, in order to collect finely resolved, micro climatic measurements on test fields and to use them later as a basis for decision-making for ecological and economic optimization issues together with our project partners. The sensor network records values for air temperature, air pressure, humidity, UV index, brightness, soil moisture, wind direction, wind speed and precipitation every 20 seconds and build and store the average values each minute.

As part of the DAKIS project, heterogeneous sensor networks are currently being operated on three test fields in Brandenburg (Großmutz with 32 nodes, Müncheberg with 10 nodes and near Wandlitz also with 10 nodes) with a total of 52 sensor nodes. The sensor networks are organized in a star topology and communicate bidirectionally in the 868 MHz band for *Short Range Devices (SRDs)*. A small solar cell ensures all year round operation of the sensor nodes. For further technical details on the sensor network and its sensor nodes please refer to [1].

The project requirements as well as the technical feasibility at the respective locations in some cases differed significantly. For example, in Grossmutz there was a protective strip for the installation and low-maintenance year-round operation of the sensor nodes. In the other two test areas, the sensor nodes had to be installed directly in the fields and needed to be temporarily removed for cultivation several times a year. There have been requests from project partners to stay flexible and to provide optional sensors and connectivity for future use for example. The requirements for our sensor network were therefore very diverse from a technical and mechanical point of view.

Therefore the concept intends three different modular hardware platforms that are equipped with different sensors and designed for capabilities. *Basic Sensor Nodes (BSNs)* are the most common ones. These are sensor nodes that were developed to measure humidity, air pressure, air temperature, UV index and brightness. An extension of the BSN is used on the test field near Wandlitz and enables the additional use of two *10-HS*[2] Soil moisture sensors. The so called *Extended Sensor Node (ExtSN)* was developed for more advanced and coordinating tasks within the network but also to handle more complex sensors and peripherals. The *Gateway* and the *Soil-Node* are directly derived from it. The gateway is the central sensor node and network management unit and also has a digital wind vane, anemometer and rain gauge. The soil nodes installed in Großmutz have the task of recording and transmitting soil moisture sensor data to the gateway. They are equipped with 6 soil moisture sensors each of them buried in a depth of 30, 70 and 100 cm with a distance of 4 and 8 meters in the field. Since the measuring process is comparatively very energy-intensive, they have no other measurement task.

[1]Project homepage: https://www.adz-dakis.com/

[2]Data sheet 10-HS: https://www.metergroup.com/en/meter-environment/products/ech20-10hs/ech20-tech-specs

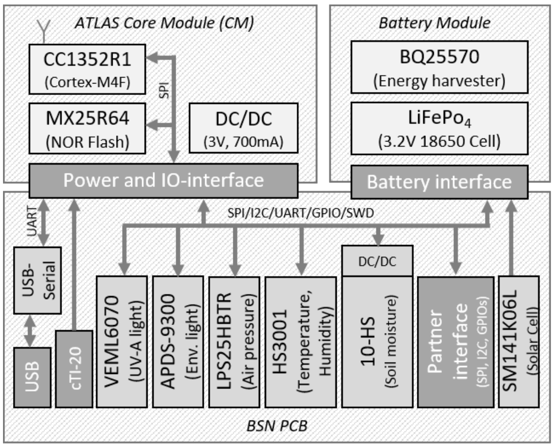

Figure 1. BSN platform architecture [1]

A key factor in the development process was the energy efficiency of the system. It was frequently analyzed and evaluated during the development process, since hardware and software decisions always had an impact on the power consumption of the individual sensor nodes [2] as well as the overall system. The first prototypes of the sensor network and strategies for energy harvesting have already been presented in [1]. Figure 1 gives an impression about the BSN platform architecture. Beside the power consumption in deep sleep, the radio frontend has also a significant impact on the energy efficiency of the BSNs. Its choice had already been made by using the processor *CC1352R*[3] from *Texas Instruments (TI)*. However, parameters such as the transmission power, baud rate, encoding, the distance between the individual sensor nodes, the antenna itself and the resulting packet loss rate have a significant impact on the power consumption [3]. This paper gives an example on how such decisions can influence the power consumption.

In section II, a short power analysis based on real measured values of the application of the BSN is presented and the measured results are assigned to corresponding system states. Section III uses this power measurement to show as an example, how the choice of antenna and selected transmission parameters can affect the packet loss rate and consequently the operating time of the system. For this purpose, a range test was carried out in which three different antennas, the transmission power, baud rate and distance were modified. The paper concludes in section IV with a short insight on two software-based approaches to save additional energy while operating the sensor network.

II. Power analysis

The BSNs are powered directly by a 3.2 V 1600 mAh LiFePo4 battery, which is recharged by a solar cell (SM141K06L with max. 184 mW) and a charging controller (BQ25570) with *Maximum Power Point Tracker (MPPT)*. However, when the sky is cloudy, the performance of the solar cell drops drastically and the daily requirement of the BSN of initially 74.85 mWh per day can no longer be covered. This case can be observed in particular during the winter period in the dark season. It can last for more than 4 weeks and so the operation must solely rely on the battery.

[3]CC1352R data sheet: https://www.ti.com/product/CC1352R

Table I
Energy consumption and active time according to the system states during one application cycle of a BSN (battery level is 3.2 V)

State	Active time in %	Average I in mA	E in mJ
Radio beacon RX	0.3365	6.724	16.5214
Radio data TX	0.1885	19.537	23.8779
Sensor controller	1.7005	0.674	9.4989
MCU Sleep	97.7564	0.384	274.6046
External memory	0.0180	3.598	0.8795

First projections have been made, based on information in the data sheets and an estimated active time in the system states from table I. They result in an average daily power consumption of 188.16 mWh and an operating lifetime of a maximum of 27 days without being recharged by the solar panel. Through numerous modifications and optimizations of the software, a daily power consumption of 74.85 mWh and thus a maximum operating lifetime of 68 days could be achieved. At the end, the power consumption could be even reduced down to 35.5 mWh per day with a maximum operating lifetime of 144 days without being recharged. A major change was to shift the periodic reading processes of the sensors from the ARM Cortex M4F core to the dedicated sensor controller integrated in the *CC1352R* and only wake up the M4F core to save the sensor values or for wireless communication. The measurement was carried out with the WISDOM measurement platform presented in [4]. The results of these measurements and the corresponding system states are shown in figure 2. This plot is used as a basis for the calculations and improvements regarding the radio transmission profiles described below.

After a short initialization phase close behind the system reset, the temporal behavior and the associated power consumption of the individual system states in this application only change in the order of ms. Considering normal operation and excluding error cases, the measurement is therefore suitable for extrapolating the systems operational time. This results in the average power consumption and active time determined in table I for the different system states in analogous to the procedure presented in [5]. It becomes apparent, that the most energy is used by far for deep sleep mode (MCU sleep) and radio communication, including beacon listening (radio RX) and transmitting the collected sensor measurement values (radio TX). The other states, such as external memory operation are almost negligible due to their short active time or cannot be recorded with the used power measurement method. The boot phase in this case is negligible and is not considered here, as it is only active once during start up.

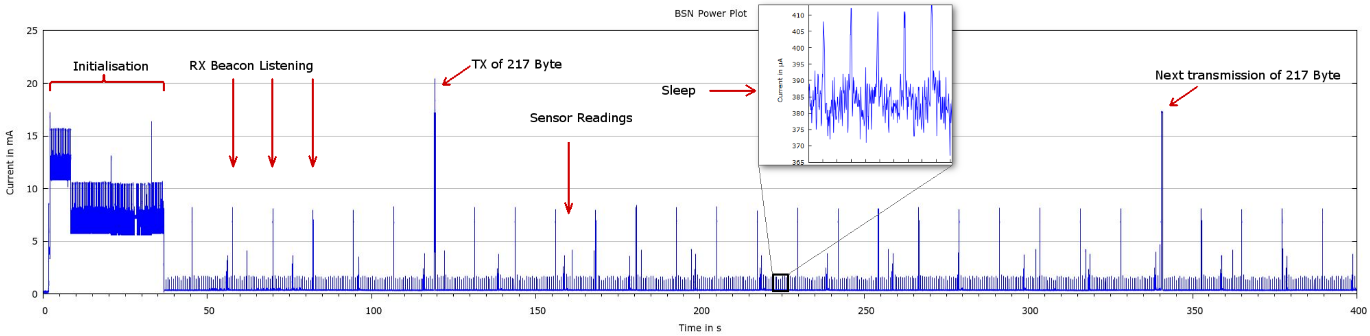

Figure 2. Power plot of a BSN with a full application cycle of 221.48 s during normal operation

III. Range test

Initially a radio configuration with a transmission rate of 5 kbps and *Forward Error Correction (FEC)* was used to increase the transmission range. It improves transmission reliability, but results in long transmission times and its associated high power consumption on the other hand and needs to be improved as well. The flexible *Molex 211140* antenna of the BSN was imposed by the node design, but the antenna on the gateway could still be modified. It was now interesting which antenna and which data rate was suitable or at least necessary for reliable transmission. Since each additional parameter would have caused the measurement time to increase exponentially, wireless communication was only examined in one direction, as is most common in normal operation (from the BSN as the sender to the gateway as the receiver). The aim was to achieve a radio link of at least 200 m with a packet loss rate of less than 10 %. This roughly corresponds to the longest distance (193 m) between the gateway and BSNs on our test field in Großmutz.

A. *Test preparation and execution*

Three antennas designed for operation in the 868 MHz frequency range were tested (IS.ACIOTANT868WRA, a 36 cm LORA rod antenna and a flexible Molex 211140 antenna). Each of them with transmission powers of 5, 10, 11 and 12.5 dbm, respectively at distances of 25, 50, 100, 150, 200, 300 and 400 m in *Line of Sight (LOS)*. The RSSI was measured, CRC errors detected and recorded and the packet loss rate calculated.

The results were mapped to the values previously captured in table I, the proportion of radio communication for the transmission of the sensor values was extracted and the active time and power consumption for the application profile recalculated. For this task, two BSN nodes have been prepared, one as a receiver (simulating the gateway) and one as a transmitter (a standard BSN in a field setup). The nodes were mounted on a tripod at a height of 1.5 m above the ground and their antennas constantly aligned in each test run. The respective transmission profiles were measured for each geographical position with direct LOS between transmitter and receiver. Only the position of the transmitter was changed during the test. The receiver always remained in the same place and orientation for the entire test, with all three antennas being exchanged and measured one by one for each distance.

A randomly selected byte sequence of 255 bytes was initially generated as the package payload and then used again for each test run. In a test run, 100 packets each with 255 bytes of generated data were sent one after the other and the packet loss rate and the average RSSI were recorded. The results were then calculated, equivalent to the states of the BSN application from table I, adapted for 217 bytes of user data and are listed in table II. A general statement about the quality of the selected antennas cannot be derived, as an antenna can only provide its optimal performance if the circuit behind it is also matched perfectly. There are also numerous other factors that can influence the packet loss rate on both the sender and receiver side. For example interference signals, reflections, the biomass or for example, the alignment of the antennas to each other also have an influence on transmission quality and the measurement results. For example, there was an unknown transmitter in the test area that was communicating in the same frequency band and blocked the channel for several seconds at intervals of about 5 minutes, apparently without first scanning the channel for active communication. In such a case, our particular test run was repeated.

B. *Experimental results*

A total of 3 profiles predefined in TI's *Smart RF Studio* were used for the test. One with 5 kbps baud rate and FEC for long distances, 50 kbps for medium distances and 200 kbps with CRC for short distances. The results are shown in figure 3 and 4. It is easy to see that the packet loss rate for the angled *IS.ACIOTANT868WRA* antenna at 100 and 150 m depends heavily on the transmission power. Reception was no longer possible with this antenna at a distance of more than 150 m, so the measurement for this antenna was suspended. With the *36 cm LORA rod antenna*, on the other hand, a packet loss rate is only recorded for a distance of 400 m. At all other positions and settings it was 0 % regardless of the data rate or transmission power. The flexible *Molex 211140* antenna reached a critical packet loss rate from a distance of 200 m and more at a baud rate of 200 kbps. For the other settings and positions, the packet loss rate was in a acceptable range. The

90 degree angled antenna *IS.ACIOTANT868WRA* was finally ruled out because of its high packet loss rate. It did not meet the requirements of at least 200 m. With the 36 cm *LORA rod antenna*, the best packet loss rate was achieved across all transmission profiles. It is very large compared to the other antennas and requires appropriate brackets and space for installation on the gateway. The flexible antenna *Molex 211140* achieved good results at 50 kbps even at 200 m.

The calculated results and effects on the daily power requirement of a BSN are summarized in table II and III. Due to the reduced transmission time by the increasing baud rate while transmitting the same amount of data, the 200 kbps transmission profile would be most suitable. Logically, this is also where the greatest potential for savings in terms of energy efficiency is possible, as long as the packet loss rate remains in an uncritical range. The faster the data was sent, the shorter the active time of the radio front end. However, the transmission errors also increased, which would lead to a new transmission attempt in the application. Also the *Molex 211140 antenna* built into the BSNs, would have already reached a packet loss rate at 200 kbps that was critical for us at a distance of 200 m. So the decision was finally made to use 50 kbps. In addition, an increased error rate has to be expected if there are more than one communication participants in the network. At 300 and 400 m, communication was no longer possible with this antenna. The influence of the radio transmission power (dbm) on the BSNs power consumption was comparatively much less but clearly measurable. The packet loss rate has not improved significantly due to an increased transmission power respectively to the measurement position. The savings in power consumption for the reduced time slot during transmission (TX) was clearly measurable. In comparison between 5 and 12.5 dbm, a potential power optimization of 22.7 % during transmission (TX) could be calculated. As the transmission time is very short, the impact on the overall power consumption is small, but still results in a difference of 12 days of extended operating lifetime for 5 dbm at 200 kbps compared to 12.5 dbm at 5 kbps.

Table II
EFFECT OF THE SELECTED TX PROFILE ON THE DAILY CONSUMPTION AT 868 MHZ, 32 BIT SYNC-WORD, 2 BYTE CRC, CALCULATED FOR 217 BYTE DATA LENGTH, MEASURED FOR THE OVERALL SYSTEM, INCLUDING MCU WITH SENSORS AT SLEEP MODE

Profile	**5 kbps**	**50 kbps**	**200 kbps**
Symbol rate in kBaud	20	50	200
Deviation in kHz	5	25	100
RX filter bandwidth	$34.1\,kHz$	$98\,kHz$	$273.1\,kHz$
Preamble count	$2\,Bytes$	$4\,Bytes$	$4\,Bytes$
Modulation	$2-GFSK$	$2-GFSK$	$2-GFSK$
FEC	$1:2$	$-$	$-$
DSSS	$1:2$	$-$	$-$
Whitening	Off	Off	On
TX active time in ms	417.600	41.760	10.440
mWh/day, 5 dbm	34.859	32.942	32.782
mWh/day, 10 dbm	35.258	32.982	32.792
mWh/day, 12.5 dbm	35.501	33.006	32.798
Diff. mWh/day	0.642	0.064	0.016

Table III
AVERAGE CURRENT MEASURED FOR GIVEN TX POWER SETTINGS

TX power in dbm	**5 dbm**	**10 dbm**	**12.5 dbm**
P_{TX} **in mW**	48.336	57.16932	62.518

IV. FURTHER MEASURES TO SAVE ENERGY DURING OPERATION

In addition to excessive use of the low-power mode, additional measures have been implemented in software to further reduce the average power consumption. A battery charge status is estimated every 2 minutes based on the battery voltage. Based on the result, the measurement intervals for the sensors are modified. If the battery is fully charged and the battery voltage is above 3.3 V, more sensor values than necessary will be taken into account. If the battery voltage is between 3.1 V and 3.3 V, the reading intervals of the individual sensors are set to the requirements mentioned in [1]. Should the battery voltage fall below 3.1 V, the BSN goes into an emergency mode. Depending on the transmission power and symbol rate, the remaining charge in the battery would only last for up to 12 days. In this case, the BSN stops sending the sensor values to the gateway and stores the readings locally on its external flash memory. This means that no data is lost and when the battery has been sufficiently recharged, the values will be transmitted to the gateway. This can prevent gaps in the series of measurements. The daily requirement drops to 31.03 mWh, which results in an additional extended operating time of 9 days with 10 % remaining battery capacity. A hysteresis of 50 mV was implemented to avoid oscillation between the threshold values.

While the daily power consumption at 5 kbps and 5 dbm differs measurable from 12.5 dbm, the difference at 200 kbps is only 0.016 mWh. At 50 kbps, however, the 0.064 mWh per day has an optimization potential of 0.2 % left, compared to the remaining consumption, which can be achieved by controlling the transmission power between 5 and 12.5 dbm. Therefore, a simple algorithm depending on the packet loss rate was implemented in order to dynamically configure the transmission power on demand between 5 and 12.5 dbm. If the packet loss rate is equal to 0 %, the transmission power is gradually reduced by 1 dbm. If the packet loss rate rises above 30 %, the transmission power is successively increased by 1 dbm. In addition to small power-saving effects, the system can thus react in changing external conditions such as growing biomass or increased humidity.

A time synchronization and the associated communication effort with the gateway is only carried out if there are deviations of at least 2 seconds from the system time of the gateway and is executed once every 10 minutes.

V. CONCLUSION

It has been shown, that small changes in software can have a major impact on the energy efficiency of a system. In particular, the use and configuration of the underlying hardware determines its energy efficiency. This depends on the

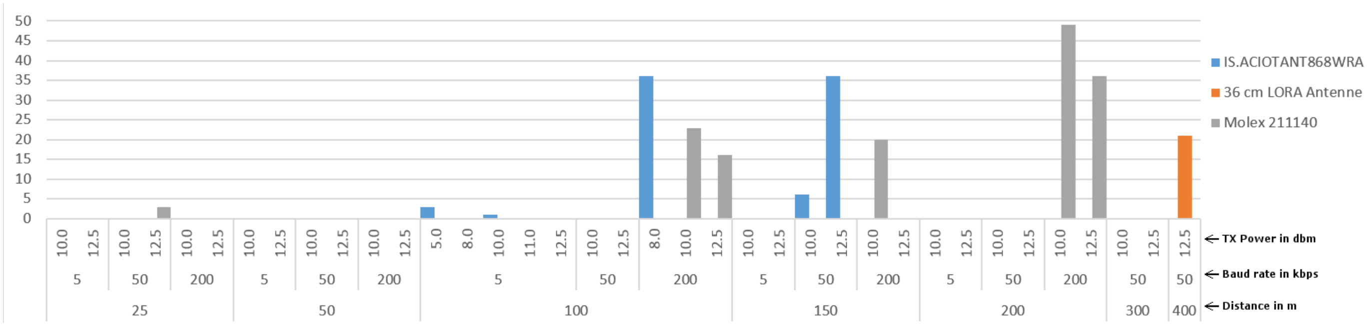

Figure 3. Results of the range test, CRC error rate depending on distance, TX power and baud rate

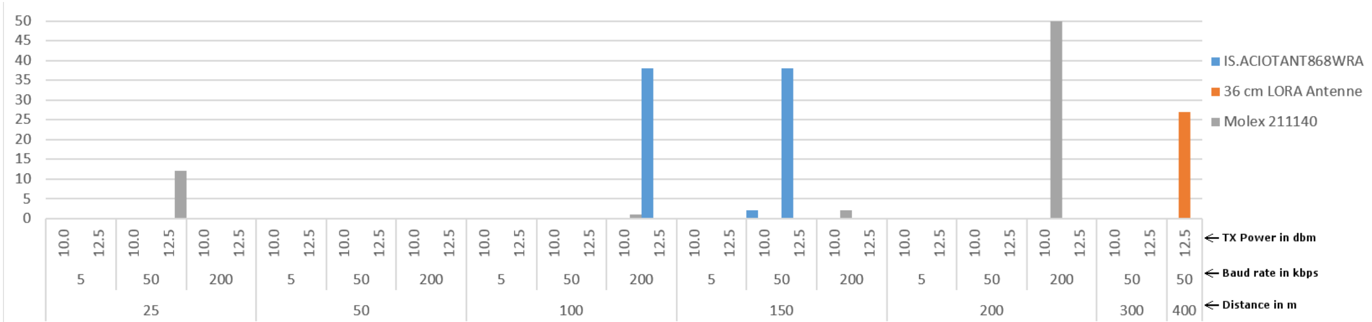

Figure 4. Results of the range test, packet loss rate depending on distance, TX power and baud rate

application respectively and must be examined and optimized on a case-by-case basis. Even changing a few parameters can lead to large differences in power consumption. Based on the range test, the average power consumption of the entire system was reduced from initially 3.12 mWh to 1.48 mWh respectively 1.36 mWh. This extended the operation time, without recharging the battery by solar cell, from 68 to 147, respectively 156 days. Taking the low battery emergency operation into account, the system can operate for up to 177 days.

The choice of antenna had an impact on transmission quality and range. Faster symbol rates reduce the active time of the radio front end and thus the average power consumption in this state. At the same time, these led to more transmission errors and a reduced range. By choosing the right antenna, a good compromise between symbol rate, range and power consumption could be achieved for our application requirements. A general savings potential cannot be derived from this experimental setup. In our example, however, we were able to finally more than half the power consumption. The sleep mode in our low-duty cycle applications now has the greatest savings potential again.

VI. Outlook

Further optimization potential lies in the sleep mode and the stabilization of the dynamic transmission power algorithm. There are still many adjustments to be made in higher application and protocol layers that need to be examined with further tests. In addition, the effects of changed system parameters of the used TI-RTOS operating system should be examined. This includes, for example, task priorities, ring buffer sizes or the configuration of the tick timer. The measurement methodology for recording the performance values with the help of the WISDOM platform will be improved and such tests automated.

Acknowledgment

This work was created as part of the DAKIS project at the IHP and was funded by the *Federal Ministry of Education and Research (BMBF)* under the reference number *031B0729C*.

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