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LONG-LIFE SENSOR MODULES – CHALLENGES FOR HARDWARE DESIGN AND MAC ALGORITHMS

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ABSTRACT

The life span of wirelessly networked sensor modules correlates directly with the principle of operation of various system layers as well as the chosen hardware design. This includes optimizing access to the wireless medium in terms of power consumption and powerefficient transmission of messages across several intermediate nodes. Further areas of concern comprise the choice of suitable hardware components such as micro-controllers, transceiver circuits, and peripheral sensorics as well as their focused activation according to the requirements of the application. This contribution summarizes lessons learned as well as potential caveats and challenges given a concrete implementation.

Index Terms - Wireless Sensor Network, TinyOS, ConSAS, Lifespan, Building automation sytems, Hardware, Software

1. INTRODUCTION

In building automation systems, simultaneously maintaining both a consequent user focus as well as cost and energy efficiency represents a fundamental challenge. Current solutions are characterized by inadequate monitoring of relevant indicators and non-transparent principles of operation. Recent technological progress in the areas of electronic components, telecommunication engineering, and information technology enable the wide-spread application of sensor networks in a broad variety of application contexts. In building automation, this leads to new perspectives for user integration, such as monitoring individuals' comfort and context-sensitive user interactivity.

The application of optimized wireless sensor-actuator networks for monitoring relevant indicators in building control applications and their integration into these systems is the subject of an ongoing F&E project [1] at the IMMS. The goal consists in creating a wireless sensor-actuator network capable of user- and scenario-specific settings concerning environmental parameters in the building in addition to intelligent logging and forwarding of sensor data.

Nowadays, a plethora of sensors is available for conceivable applications in the context of building automation. They keep windows and doors under surveillance, monitor the temperature of radiators and rooms, humidity, power consumption of electric devices, CO and CO2 concentrations in the air, or illuminance, to name just a few. According to the specific requirements, it may be necessary to employ multiple sensors in order to measure a single indicator adequately. Consequently, the number of sensors in a building tends to be very large.

As connecting all of these sensors to the mains is prohibitively involved, power has to be provided through (rechargeable) batteries. Changing batteries is too time- and cost-intensive to be performed on a frequent basis. This leads to the requirement of a long time of operating using a single set of batteries. This duration is also referred to as lifespan.

This contribution details the measures taken in a specific project aimed at realizing a long-life wireless sensor network, and how to estimate the expected lifespan. Section 2 will introduce the architecture of the sensor nodes' software. Section 3 will give a review of the hardware. Section 4 will explain the optimized access to the wireless medium. The role of the routing protocol during the transmission of messages over larger distances will be described in section 5. Finally, section 6 will estimate the expected lifespan of a wireless sensor node.

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2. SYSTEM LAYERS

All Based on the IEEE 802.15.4 standard [2], a large number of wireless sensor nodes is offered by a variety of vendors. These are able to communicate with each other, send messages, or relay data to other nodes thanks to the common Medium Access Control (MAC), frequency range, and modulation scheme.

The TinyOS operating system provides a Hardware Abstraction Architecture significantly facilitating both porting the operating system to a specific hardware and the utilization of a system's components by applications (fig. 1). Furthermore, the integrated power management of the operating system core determines those components required at any specific time and switches the microcontroller to the best-suited power saving mode.

It is the responsibility of the application layer to uniquely identify modules including their sensors and actuators. A system has been implemented which enables the identification of different modules, thus significantly simplifying the configuration of systems, actors, and actuators as well as adjustments of parameters of the MAC and routing protocol. In addition to this, the concept includes the notion of creating virtual sensors using the measurements of several individual sensors (see fig. 1).

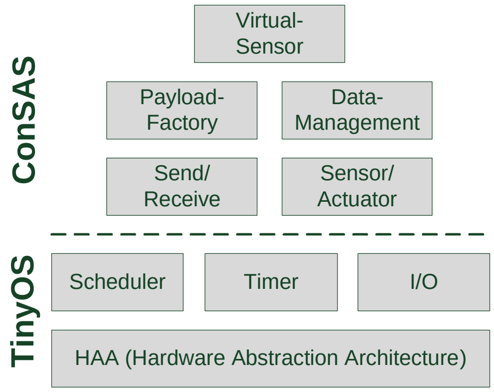

Figure 1: System architecture

In summary, the combination of TinyOS and the IMMS-developed ConSAS application software and Gateway Application Framework [3] is characterized by the following benefits:

- easy change of the target platform
- integration of sensor nodes with different sensors in a single Network
- compatibility of transceiver circuits at the MAC layer
- automatic, situation-dependent power management

3. HARDWARE DESIGN

For evaluation purposes, a minimal sensor node has been designed and assembled. Its system core consists of the microcontroller-transceiver combination ZigBit [4]. ZigBit modules are comprised of:

- the ATmega1281 low-power microcontroller
- the AT86RF230 2.4 GHz IEEE 802.15.4 transceiver

In addition to the microcontroller, the module includes a 32 kHz low-power crystal oscillator which allows for an adjustment of the internal RC oscillator or the implementation of an RTC. The transceiver is complemented by an oscillator and discrete components for antenna matching. The module employed achieves a small overall size while maintaining decent HF characteristics through the use of chip antennas.

The radio module is supplemented by sensors (illuminance, humidity, temperature, CO2, if necessary), a pushbutton, and a flash chip serving as data and configuration store (fig. 2 and 3).

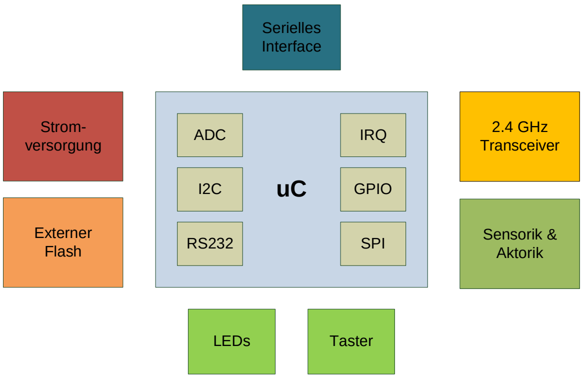

Figure 2: Basic composition of the wireless sensor node

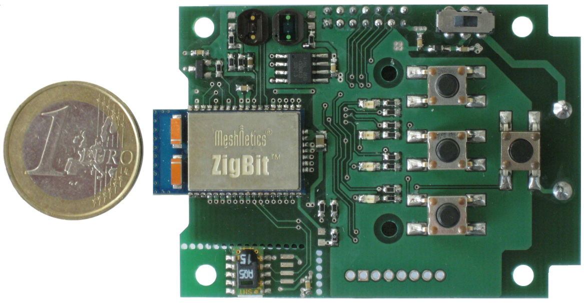

Figure 3: Size comparison of the sensornode to 1€

4. OPTIMIZING ACCESS TO THE WIRELESS MEDIUM

If one is to compare the specification data of a sensor node's individual components, the transceiver circuit and microcontroller, followed by the sensors, will be the foremost power consumers. It is thus advisable to only activate the transceiver circuit when necessary. This can be achieved through smart sampling of the radio channel [5], synchronization of networking peers, or through the application of TDMA, a multiplex scheme for signal and message transmission. Each of these approaches strives to minimize the time spent in transmit (Tx) and receive mode (Rx). Nevertheless requirements such as relaying of messages from other nodes, QoS constraints, or even real-time operation may need to be considered.

The ConSAS application software developed at the IMMS enables the operation of a cluster tree network (see fig. 4) as an alternative to B-MAC, a networking protocol for sensor networks, in low-power listening mode. In a cluster tree network, each cluster is managed by a cluster head with a permanent power supply for sensors and actuators with higher power requirements. It furthermore forwards its sub-nodes' data, i.e., the data of wireless sensor nodes gathering measurements in a highly energy-efficient manner, to pre-determined destinations. The sub-nodes enable their transceiver circuits for only very short periods of time in order to transmit their data and dynamically adapt their transmission power according to the cluster head to be reached.

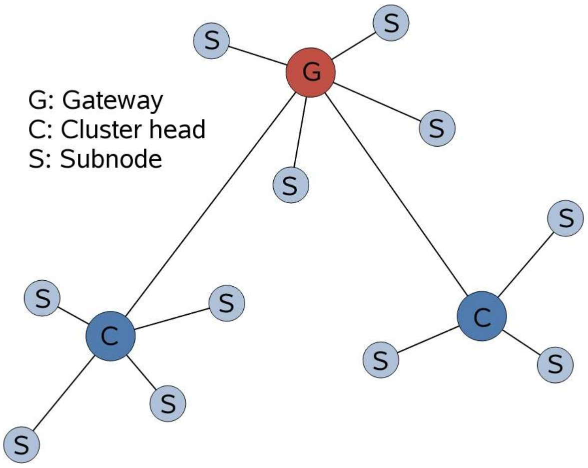

Figure 4: Cluster tree network

5. TRANSMISSION ACROSS INTERMEDIATE NODES

If distances larger that the reach among two nodes are to be bridged, data inevitably has to be routed across intermediate nodes or dedicated relays. Similarly to traditional networks, the routing choices across such intermediate stations are made by a routing protocol. It is based on a metric determining the next hop towards the final destination. Common metrics are the shortest distance or best radio link quality to the destination in question. Energy-efficient routing protocols also take into account the power required for transmit and receive operations as well as the power currently available in the intermediate station.

The metric of an energy-efficient routing protocol [6] should thus, subjectable to scaling functions, include the following parameters:

- sum of the costs of all intermediate stations on the way to the final destination
- transmission power required to reach a neighboring node
- packet error rate (PER) of the chosen link
- delay

6. LIFESPAN

The lifespan of a sensor node is predominately affected by four factors:

- power consumption and time required for sensor read-out
- power consumption and time required for transmitting the data
- power consumption and time required for receive operations
- frequency of these events
- power consumption in sleep/idle mode

These factors illustrate the strong correlation of lifespan as defined in this contribution, the application scenario, and hardware requirements. Therefore, an application scenario has to be defined in order to estimate the lifespan.

The wireless sensor network has been conceived as a cluster tree network. For the sensor nodes, this means that they are able to unimpededly transmit their data to the cluster head. They do not have to relay data from other nodes. The estimated lifespan is calculated for varying combinations of sensors.

6.1. Power Supplies

In a first step, the capability of different power supplies has been examined [7]. In this project, the sensor nodes have been designed to be suppliable by AA cells. In a wireless sensor node, there is a constant alternation among active and passive phases with very low power consumption. Consequently, a low self-discharge significantly extends a sensor node's lifespan. Batteries of type HR-3UTG [8] have been used during the development of the sensor node due to their low self-discharge compared to many other rechargeable batteries available. These batteries are designed for a discharge current of 4 A. A discharge current of 20 mA is significantly below this value. The sensor nodes each require two of these batteries in series. Measurements have therefore been performed with two of these rechargeables connected in series. Figure 5 shows the recorded discharge curve.

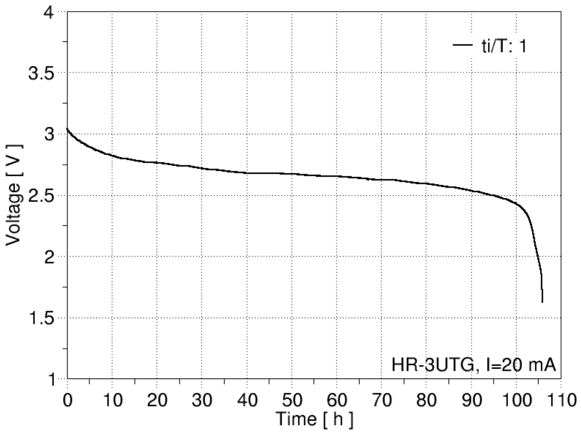

Figure 5: HR-3UTG discharge curve

The ATmega1281 microcontroller employed in the sensor nodes requires a minimum operating voltage of 1.8 V [4]. For this reason, the capacity actually usable has been calculated in relation to the minimum operating voltage; figure 6 displays the result. The capacity of HR-3UTG-type rechargeables is approximately 2240 mAh if used in the sensor nodes.

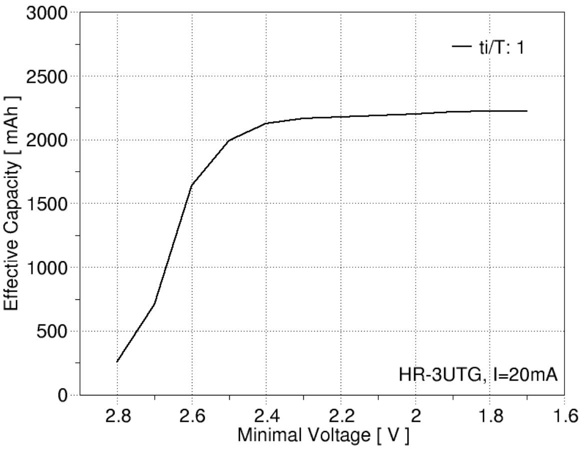

Figure 6: Effective capacity of HR-3UTG-type batteries

In order to be able to also create smaller nodes, it became necessary to look for an alternative power source, leading to the choice of a CR2477-type Lithium battery. Its size corresponds roughly to the dimensions of three 1-Euro coins stacked on top of each other. Despite this diminutive size, it features a capacity of 1000 mAh and a low self-discharge. It is, however, designed for a discharge current of only 1 mA and would, if continually discharged at 20 mA, allow for an operation time of no more than a few hours. Figure 7 shows this as the line marked circles.

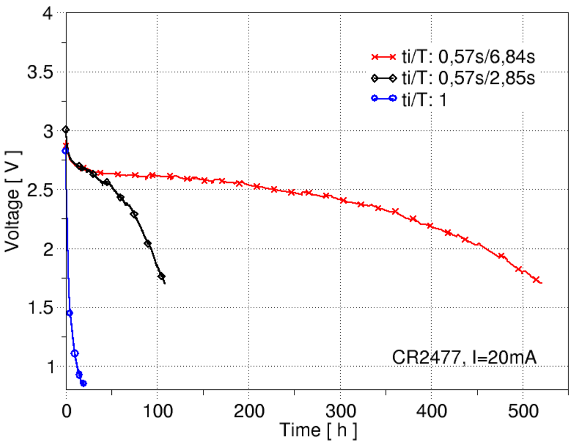

Figure 7: CR2477 discharge curves

However, this is not the mode of operation exhibited by the sensor network. During normal operation, measurements are to be performed discontinually, with pauses in between individual measurements which allow for the battery to recover. This is illustrated by the two additional curves in figure 7.

The effective capacity of CR2477-type batteries has been calculated in analogy to HR-3UTG-type batteries. The result is shown in figure 8 and amounts to approximately 912 mAh.

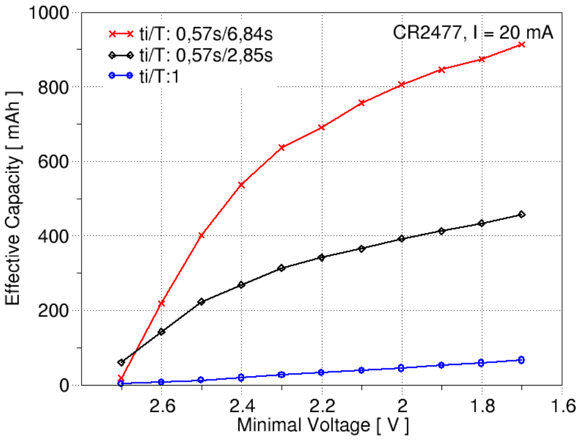

Figure 8: Effective capacity of CR2477-type batteries

In the following section, the lifespan estimation will be limited to the CR2477 battery. If wireless networks are to be operated for extended periods of time, non-rechargeable Alkaline batteries are to be preferred over HR-3UTG-type ones. In the form factor of the HR-3UTG battery, they are available with capacities of up to approximately 3000 mAh. HR-3UTG-type rechargeables are subject to a self-discharge of approximately 15% to 30% per year [8]. In contrast to this, the self-discharge of non-rechargeable Alkaline batteries is approximated at only 4% [9]. This leads to an increase of the estimated lifespan by a factor of 3 compared to CR2477-type batteries.

6.2. Power Consumption of a Device

In a subsequent step, the power consumption during the individual activities of the sensor node has been measured. To this end, the node in question was programmed as a sub-node. By toggling two port pins, activities of interest of the sensor node were indicated. A resistor of less than 1 Ohm was soldered into the sensor's power supply line, and the voltage drop across this was measured. The voltage curves have been made visible using an oscilloscope (fig. 9).

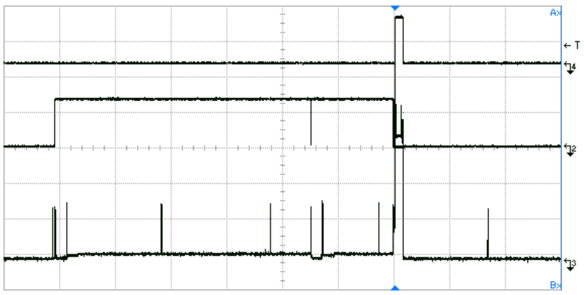

Figure 9: Read-out of sensors and transmission of the data

The top curve establishes the time needed to transmit the data via the wireless interface.

The middle curve of figure 9 visualizes the time needed to read out the sensors. Even though four sensors are being read out, only two intervals can be made out. The left-hand interval corresponds to the time taken to read out the temperature sensor. This process takes the largest proportion of time. The subsequent interval marks the read-out of the humidity sensor. The time required to read out the illuminance sensors is so short as to be obscured by the right-hand falling edge.

The bottom curve shows the power consumption of the sensor node during the activities. It is evident that the time required to read out the sensors is several times longer than the time required to transmit the resulting message.

Tables 1 and 2 sum up results of the measurements.

Transmission of Data	18,1 mA
Read-out of sensors	1,0 mA

Table 1: Power consumption of individual activities

Transmission of data	8,5 ms
Read-out of the temperature sensor	229,3 ms
Read-out of the humidity sensor	74,0 ms
Read-out of the PAR illuminance sensor	0,3 ms
Read-out of the TSR illuminance sensor	0,3 ms

Table 2: Duration of individual activities

6.3. Lifespan of a CR2477-powered Device

In order to predict the lifespan of a sensor node, the power consumption per day was calculated for each of its sensors, considering the intervals in between individual read-outs. A summation of these values yielded the daily power consumption.

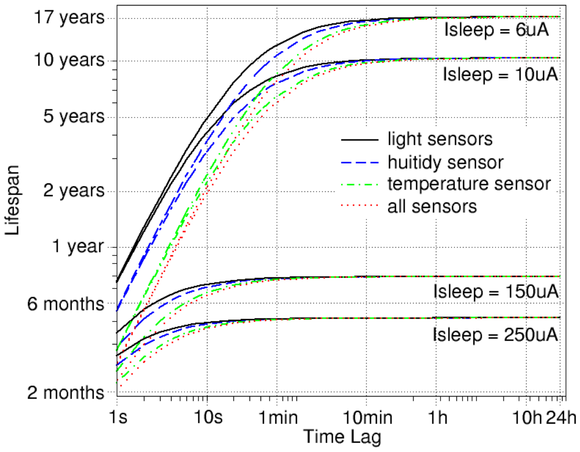

Figure 10: Lifespan of a sensor node

On this basis, the lifespan of a sensor node can be estimated. The result is shown in figure 10. It is clearly visible that the standby current has a discriminating influence on the lifespan of a sensor node. The order of the individual curves corresponds to the order of elements in the key of figure 10.

A standby current of 10 µA can only be achieved with select specimens. Depending on the intervals in between the activities, it seems realistic that a CR2477-type Lithium battery will be able to supply the examined sensor node for a duration of 5 through 10 years.

7. SUMMARY

This contribution has introduced a wireless sensor network which was specifically developed for applications in building automation. Sections 2 and 3 have introduced the software and hardware of the sensor nodes; sections 4 and 5 have pointed out ways to realize an energy-efficient wireless network. Section 6 has shown that a wireless sensor node can be powered for extended periods of time even with a CR2477-type Lithium battery. If the conditions detailed in that section are maintained, a lifespan of up to 10 years is to be expected.

8. ACKNOWLEDGMENT

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