A Simulation Model for WBSN Protocol Design

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***Abstract*—A Wireless Body Sensor Network (WBSN) is a wireless network made of small, light and unobtrusive sensor nodes which are attached to the human body. These sensors permanently record vital signs. WBSNs can be used to monitor the medical condition of patients over a long time with high accuracy.**

To conserve energy and enable long operating times, WBSNs have to be customized to the specific use case. This work presents the detailed energy and simulation model of a transceiver to support the development and optimization of application specific WBSNs. It provides a set of tools to simplify the WBSN protocol design.

I. Introduction

The report in [1] shows that most causes of death in Germany are related to diseases of the cardiovascular system. Several of these deaths could have been prevented by a detailed analysis of the patient's vital signs and an early intervention.

To be able to analyze and track the physical condition, data has to be gathered from the patient by a technical system. Different vital signs like heart rate, electrocardiogram (ECG), blood oxygen saturation (SPO2), electroencephalogram (EEG), respiration rate, body temperature, activity, etc. are clinically relevant.

This introduces the concept of personal long-term vital sign monitoring systems. Besides activity tracking, their main areas of application include the permanent monitoring of high-risk patients in their daily live and the monitoring of patients after surgery. Such a system should be used every day and for a long period of time to track changes and detect rare but relevant events. In this way, the system can help to start an early therapy and prevent hospitalizations or live-threatening emergencies [2].

One possible way to realize such a technical system for non-obstructive vital sign recordings are *Wireless Body Sensor Networks* (WBSNs). A WBSN consists of a number of small network nodes attached to or even implanted inside the human body [3]. The nodes use specialized sensors to record vital signs and communicate with each other using radio communication.

Fig. 1 depicts one possible autonomous WBSN that could be used in the above-mentioned scenario of a long-term personal monitoring system. In this example, three individual sensors record EEG, activity and SPO2 and transmit the data to the central network controller. This central node is responsible for filtering, (pre-)analyzing and storing the data for a later off-line analysis.

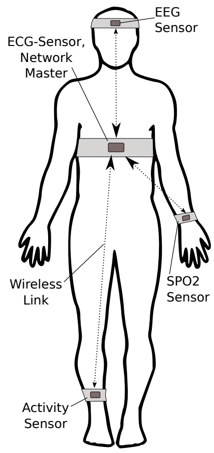

Fig. 1. Example of an autonomous Wireless Body Sensor Network that records vital signs.

One of the main problems when designing WBSNs is the energy consumption of popular radio communication protocols like WiFi, Bluetooth or ZigBee. These multi-purpose protocols were designed for completely different use cases like high speed data transmission, home automation or video streaming with little focus on low energy consumption. Especially in the application scenario of WBSNs, the available energy is the main limiting factor that restricts the solution space. The improvement of battery technologies cannot keep up with the increasing energy demands for radio communication and algorithms [4]. Using bigger batteries is not an option since this contradicts the requirement for small and lightweight sensor nodes that are convenient to use for a long period of time.

Giving up the general purpose character of the wireless network, we are able to design truly energy efficient systems by adapting the communication concepts for a specific application scenario. Therefore, the task of the WBSN designer is to find a reasonable compromise between functionality, usage duration and node size. This has to be done again and again for each new use case, combination of sensors or protocol to find an optimum. Today, no tools exist to support the network designer with this task.

II. Implementation

After analyzing several transceivers for WiFi, Bluetooth, ZigBee and proprietary protocols with a special focus on energy efficiency, the transceiver nRF24L01 [5] was selected

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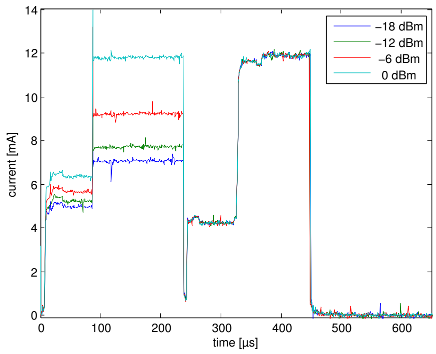

Fig. 2. Current consumption of the nRF24L01 for a single packet transmission for different output power levels.

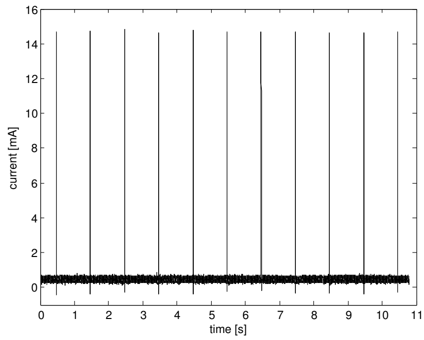

Fig. 3. Current consumption of a sensor node while periodically transmitting vital signs.

for our WBSN hardware. The nRF24L01 is a packet oriented transceiver working in the 2.4 GHz ISM band with a net data rate of 2 MBit/s and a comparatively low energy consumption.

A. Transceiver Energy Model

To design a detailed model of the transceiver that can be used for protocol design, it's energy consumption has to be analyzed in all operational states and for all possible configuration parameters. This was done using a 1.25 MSample/s USB data acquisition device and a measurement resistor on our prototype hardware. The current consumption was calculated from the high resolution differential voltage measurement across the resistor and the known resistor value. The example in Fig. 2 shows the measurement results of an experiment that kept all but the transceiver output power configuration constant when transmitting a single frame.

Measurements were carried out with several hardware nodes and in many different configurations. Comparing the measurements with the values given in the product specification, we found the average currents slightly different, especially in the settling states. It is worth noting, that the average current during TX settling is not constant as stated in the product specification, but depends on the output power configuration of the transceiver. Furthermore, we found significant discrepancies in the timing behavior between specification and hardware. Using an energy model, that is only generated based on the specification, can lead to inaccuracies of up to 20 percent in the energy calculation of a single packet.

Based on the measured average currents and the timings, a C++ implementation of the energy model was created. It can calculate the consumed energy for an arbitrary number of transmitted bytes and a given set of configuration parameters.

The C++ energy model is used in two main fields: First, it can be directly integrated into the node firmware. As a result, the sensor node can calculate the consumed energy for each transmission. This enables the use of energy aware application strategies. Second, the model is used as a reference system for the implementation of the simulation model that is described in the next section. During development, all simulation results were compared with the static C++ model to verify the correctness of the simulation model.

B. Network Simulation

The WBSN network simulation was implemented using the MiXiM framework [6], [7] in version 1.2. MiXiM is a simulation framework for wireless networks. It is based on OMNeT++ 4.1 [8], a powerful discrete event simulation framework. MiXiM uses a layered approach in the style of the OSI-model. The two lowest layers (PHY, MAC) represent the transceiver model. They had to be implemented to match the real transceiver.

To exactly model the nRF24L01, MiXiM's original radio model, which consists of the three states *Sleep*, *Transmit* and *Receive* [9], had to be extended by the new state *Power Down*. This extension enables the analysis of different sleeping strategies by means of simulation experiments. Furthermore, the capability to calculate the consumed energy has been integrated directly into the new physical layer.

To calculate the energy consumption in the model, the transceiver is treated as a *Finite State Machine* (FSM). The transceiver can be in one of several states (RX, TX, Sleep, Power Down). The transition from one state into another might or might not consume time. Each state and each transition has a typical average current consumption. The final energy consumption is calculated from the average current, the system voltage and the time that was spent in the state or transition. This approach results in a very precise tracking of the energy consumption for every state.

While the PHY layer basically models the transceiver's physical properties, the MAC layer is responsible for the functional behavior. The main task of the MAC layer is to control the media access. It defines the time a transmission starts and ends, the data rate and the transmission power. To do so, the MAC implementation uses different algorithms to trigger state transitions of the new *RadioModel*-FSM at the correct time and in the necessary order. Furthermore, the MAC layer is responsible for securing the data transmission with the automatic retransmit mechanism (ART).

III. Results

A. Example I: Periodic transmission of vital signs

A typical scenario in a WBSN is the periodical transmission of vital signs. The sensor has to transmit a measured value

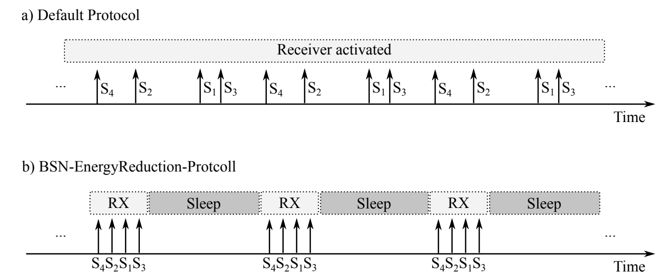

Fig. 4. Comparison between normal (a) and energy optimized (b) operation of the network master.

(e.g. body temperature) in fixed intervals (e.g. every second). To demonstrate the potential of application specific protocol designs, a real WBSN was built for this application scenario. The communication protocols were tested and optimized using the new simulation model.

Fig. 3 shows the results of an experiment with our sensor node that sends measurement data to the master every second. The average current consumption is only 460 µA. When actually transmitting data, the current consumption increases to 15 mA for a very short time.

The same scenario was implemented for a Bluetooth module and a XBee module, resulting in average current consumptions of 20.3 mA (BT) or 53.2 mA (XBee).

The rechargeable lithium polymer battery Varta LPP 422339PL with a nominal capacity of 355 mAh was assumed for the estimation of the operating time. The expected operation times are: 17.5 h when using the Bluetooth module, 6.7 h when using the XBee module and 772 h when using the prototype hardware with the optimized WBSN firmware. The energy consumption of the application processor was not considered in this calculation.

We could show that our application specific system performs much better than other more frequently used systems in a typical WBSN scenario.

B. Example II: Reduction of Idle Listening

Our WBSN concept utilizes simple star topologies to reduce the complexity of network management. This has the drawback that the master needs much more energy than the sensor nodes. This is due to the fact, that the master does not know, when the next packet will arrive. Fig. 4a shows, that the receiver is activated permanently (*Idle Listening*). This can be a problem especially for battery powered master devices in autonomous body networks.

To reduce the energy consumption of the master, we designed a new BSN protocol using the WBSN simulation framework. The protocol introduces an active phase that aggregates the transmissions of all slaves. In the inactive phase, the master can enter the sleep mode (Fig. 4b).

This approach needs some kind of time synchronization for all devices. A global real-time synchronization would be to energy costly due to the need to permanently transmit synchronization packets. In the new protocol, the master coordinates the time synchronization by only transmitting correction messages to the slaves when necessary.

The master starts with a scanning phase with permanently activated receiver, analyses the arrival times of the messages in a millisecond resolution and sends out correction packets to adapt the transmission schedule of each slave. After this, the network enters the normal operation mode and the master can go to sleep within the inactive period to save energy. The master still tracks the arrival times of all messages and sends out correction information as ACK payload whenever necessary. A new scanning period is started in longer intervals to find new or lost devices.

Using this protocol results in an energy reduction of 75% for the master in the selected scenario at the cost of a negligible increase of energy consumption at the slave devices for the reception of correction messages (0.5 µJ/message).

IV. Summary

Autonomous wireless body sensor networks represent new concepts of recording and analyzing vital signs on a personal level. The main challenge can be found in the very limited energy resources. This results in the need to adapt the network protocols to the application specific requirements and available sensors.

This paper presented a simulation model to simplify and speed up the design, evaluation and optimization of application specific wireless body sensor networks. It could be shown, that our application specific body networks perform much better (longer) than networks using standard protocols (e.g. Bluetooth, ZigBee, etc.).

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