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An Energy Model of the Ultra-Low-Power Transceiver nRF24L01 for Wireless Body Sensor Networks

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***Abstract*—In the recent years, Wireless Body Sensor Networks (WBSNs) attracted much attention in the research community. The key to success for WBSNs is the utilization of highly efficient transceivers and the application of intelligent policies to handle the limited (energy) resources. Simulations are a frequently used tool to evaluate different policies and analyze the performance of wireless networks in different configurations. The nRF24L01 is an ultra-low-power transceiver for the 2.4 GHz frequency band which is very well suited to build simple but efficient WBSNs. This work presents a detailed simulation model of the nRF24L01 for MiXiM, a simulation framework for wireless networks. The implementation is focused on tracking the transceiver's energy consumption in operation. The presented simulation model is a valuable tool for network designers and implementers when working with the nRF24L01.**

***Keywords*-Wireless Body Sensor Networks; WBSN; Simulation; Energy Model; Energy Consumption; 2.4 GHz ISM;**

I. INTRODUCTION

Wireless Networks consisting of nodes inside or in close proximity to the human body are often called *Wireless Body Sensor Networks* (WBSNs). They are frequently used in the medical area (Patient Area Networks) or in the wellness/sports sector (heart rate monitors, step counter, etc.). A common scenario is the recurrent wireless transmission of biosignals to a bedside monitor or to a central node directly worn by the patient. Signals that frequently can be found transmitted wirelessly in medical applications are: *Electrocardiogram* (ECG), heart rate, SPO_2, *Electroencephalogram* (EEG) or blood pressure. Figure 1 depicts the concept of an autonomous WBSN with several sensors.

Many restrictions apply to the design of WBSN hardware. A sensor node has to be small in its physical dimensions. Usually several different sensors have to be worn by a patient at different locations of the body. The restrictions in size go hand in hand with limited battery capacities. Only small and light, possibly rechargeable, batteries can be used for wearable sensor nodes. In many cases the radio consumes the majority of the available energy. So this is the field in that optimization can result in the biggest benefit. The design of extremely energy efficient wireless communication systems can be seen as the key challenge for the success of WBSNs.

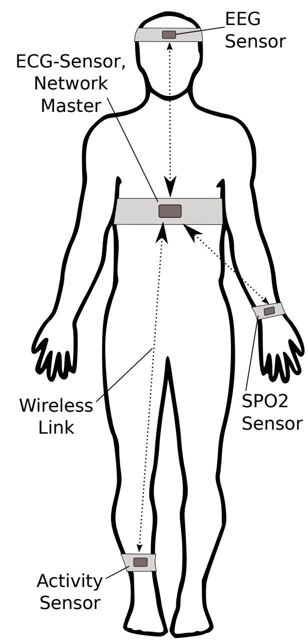


Figure 1. Wireless Body Sensor Network

A transceiver that can be used for building the sensor node hardware is the *Ultra-Low-Power* (ULP) transceiver nRF24L01 [1] by Nordic Semiconductors. This transceiver is a packet oriented radio chip working in the 2.4 GHz ISM band with a net data rate of 2 MBit/s. The transceiver stands out by a very low energy consumption and a small protocol overhead compared to other frequently used *Wireless Sensor Network* (WSN) transceivers as the CC2420 [2] or, for example, Zigbee hardware. The nRF24L01 supports two different modes of operation: *Primary Transmitter* (PTX) mode and *Primary Receiver* (PRX) mode. PRX devices are hereinafter referred to as master, PTX devices as slaves. The two modes can be used to set up a network in star topology: a central node (master) and up to six associated sensor nodes (slaves). Several autonomous networks, e.g. for different patients, can co-exist in the same physical area when using a different address configuration. The star topology is ideally suited for WBSNs: the complexity and protocol overhead can be reduced, routing is not necessary. Finally, this can result in a very energy efficient system.

Network simulations are an essential tool when designing and implementing WBSNs. A detailed simulation of the network behavior can help the system designer to decide between different strategies of operation and find performance bottlenecks or design weaknesses that are hard to analyze in a deployed system. In many cases a simulation is the only option, e.g. if the hardware is not (yet) available or if simultaneous measurements of physical parameters on many hardware systems is too costly.

The contribution of this work is a detailed model of the nRF24L01 to simulate the behavior and energy consumption of the transceiver part in a WBSN. The model was written using the MiXiM framework [3] in version 1.1. MiXiM is a simulation framework for wireless networks. It is based on OMNeT++ 4.0 [4], a powerful discrete event simulator framework.

The remainder of the document is structured as follows: In chapter II we review relevant related work. In chapter III we describe the simulation model, starting with the concept and followed by the details of the implementation. Chapter IV shows some experiments with the new simulation model. Finally, we conclude in chapter V.

II. Related Work

The transceiver nRF24L01 is used in several WSN or WBSN hardware platforms [5]–[7]. This circuit is accepted as a very efficient ULP transceiver for special application scenarios.

There are many different energy models for a wide range of transceivers: [8] proposes an analytical model of IEEE 802.15.4 slotted CSMA/CA. This model can be used with the data from [2] to calculate the energy consumption of a typical WSN transceiver (CC2420). The simulation model in [9] uses an approach similar to the here presented implementation to model a four state transceiver in OMNeT++. Additionally, the authors provide a very simple energy model for the application CPU. Their work demonstrates the simulation of the IEEE 802.15.4 protocol implementation, calibrated with the Mica2 hardware. The authors of [10] propose another energy model based on finite state machines. It can be used for on-line accounting of the energy consumption to make the sensor nodes energy aware.

The MiXiM framework for simulations of wireless systems was introduced in [11]. The details of the Physical Layer implementation are described in [12].

Energy consumption estimation is a common task in simulations of wireless networks, therefore several frameworks exist. Examples for OMNeT++ are: *Battery Module 2.0* [13] or *Energy Framework V0.9* [14]. The latter was ported to OMNeT++ 4.0 and is part of MiXiM 1.1 now.

To our knowledge this is the first paper presenting a simulation model for the ULP transceiver nRF24L01.

III. Simulation Model

A. System Concept

A typical WBSN node design consists of a microcontroller, an energy supply (battery), sensor hardware and a transceiver. It's obvious that a WBSN node is more than just a transceiver, but the transceiver might very well be the unit consuming the larger part of the available energy resources. This is one of the reasons why this work looks only at the impact of the transceiver subsystem. All other subsystems have to be optimized as well to get an efficient WBSN node, but this is out of the scope of this document.

The idea of this project was to implement a MiXiM model for the nRF24L01 since it is used in several of our hardware platforms. The transceiver has a rather limited set of configuration options, so that we could implement a nearly feature complete model to allow very detailed simulations. A detailed simulation can be utilized to simplify protocol design and verification without the time consuming processes of firmware implementation, test-bed setup and verification on the physical WBSN nodes.

The model focuses on two different aspects: The behavior and the energy consumption of the transceiver. The modeled behavior includes timings, state transitions, address handling, etc. of the hardware and is used to verify the functionality of a protocol implementation. The second main aspect, the energy consumption, is not essential for the function of the simulation but a valuable tool for the optimization of WBSNs. This is the feature that is used to maximize the network lifetime for a given set of parameters. 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, Standby, etc.). The transition from one state into another might or might not consume time. Each state and each transition is connected to an average current consumption. The energy consumption is calculated in combination with the system voltage and the time that was spent in the state or transition. Further details of the implementation will be discussed in chapter III-B1.

As mentioned in the introduction, MiXiM is a discrete event simulation framework for wireless networks. It uses a layered approach in the style of the OSI-model. Each layer has a control interface and a message interface to the upper and the lower layer. The message interface is used to move the specific payload through the layers, e.g. received packets or packets to be sent. The control interface is used for all other inter-layer communication that is not to be sent via the radio. This includes configuration commands, status reports et cetera. All modules are written in C++ and can be further configured using text files.

Besides the different layers, MiXiM uses several other modules to perform special tasks: a *World* module, defining the physical positions of all nodes, a *Mobility* module, responsible for node movements, a *Battery* module, rep-

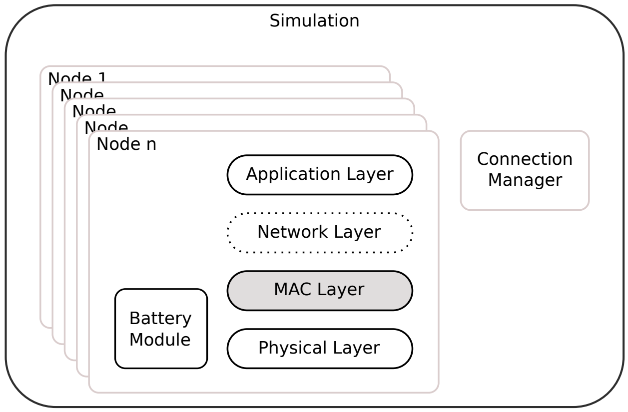


Figure 2. The simulation environment in MiXiM

resenting the power supply of the WSN node, and the *ConnectionManager*. The latter is one of the central modules in MiXiM, responsible for computing the maximum range of a wireless link between two devices. The decision is based on a simple path loss model and the transceiver characteristics. Modules that can not communicate are not connected in the simulation and thus messages do not have to be evaluated. This significantly improves the simulation performance for bigger networks. Further details regarding the *ConnectionManager* can be found in [11].

The MiXiM setup that was selected for this simulation is shown in Figure 2. Each node consists of four layers (Application Layer, Network Layer, MAC Layer and Physical Layer) and a battery module.

The *Application Layer* represents the application software that is executed on the microcontroller. The *Network Layer* is trivial for the selected scenario, since no routing is necessary for the considered star network. Therefore, the task of this layer is basically forwarding messages and control information from the application layer to the MAC layer and vice versa. Due to the simplicity of this layer it will not be further discussed below. The *MAC Layer* is highlighted in Figure 2 since it contains the biggest part of the model code. This layer combines most of the logical functionality of the transceiver: media access, automatic retransmits, timeouts, *acknowledgment* (ACK) packet generation and address management. The main components of the *Physical Layer* are the decider module, the analogue model and the radio model (see [12] for details).

B. Implementation

1) Physical Layer: This simulation uses the default implementation provided by MiXiM for the decider module and the analogue model. In this case, the analogue model is a simple free space path loss model. The decider uses a SNR threshold to categorize incoming signals into wanted signals or noise. The *Radio* module had to be re-implemented to match the features of the nRF24L01 transceiver. Figure 3 shows the FSM model that was used in the new physical layer implementation. MiXiM's original radio model, which consists of the three states *Sleep*, *Transmit* and *Receive*, had to be extended by the new states *Power Down* and *Undefined*. *Power Down* is a state with very small energy consumption at the cost of longer start-up times. *Undefined* is only used to model the correct power-on-reset timing. In contrast to the original implementation, our model limits the transitions between different states to such transitions that are possible in the real hardware.

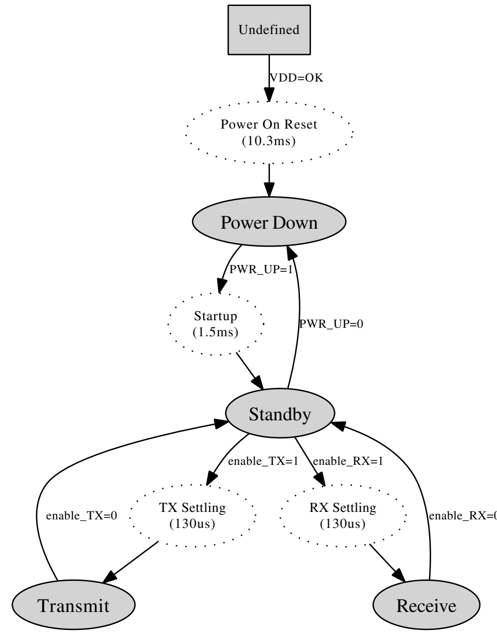


Figure 3. The extended radio model used in the physical layer.

Table I
AVERAGE CURRENT CONSUMPTION IN DIFFERENT STATES OF OPERATION.

State/Transition	Average Current	Duration
Power-On-Reset	-	10.3 ms
Power Down	900 nA	-
Standby	22 μA	-
Startup	285 μA	1.5 ms
TX Settling	8.0 mA	130 μs
RX Settling	8.4 mA	130 μs
RX (1/2 MBit/s)	11.8/12.3 mA	-
TX (0/-6/-12/-18 dBm)	11.3/9.0/7.5/7.0 mA	-

Table I shows the current consumption within each state at a system voltage of 3.0 V and the duration of transitions. These values were taken from the transceiver specification [1, p.14]. The duration of states depends on the application and is calculated when running the simulation.

To reduce the configuration complexity and prevent misconfiguration, some of the parameters (sensitivity, transition times, etc.) of the base implementation were hard-coded to the correct values for the nRF24L01.

2) MAC Layer: The MAC layer represents the algorithms that are part of the nRF24L01 hardware. The actual MiXiM implementation supports the following features of the nRF24L01:

- Variable Payload Length: 1 to 32 Byte
- Configurable number of CRC-Bytes: 1 or 2 Byte
- Configurable number of Address Bytes: 3 to 5 Byte
- Configurable voltage: 1.8 to 3.6 Volts
- Data Rate: 1 MBit/s or 2 MBit/s
- Configurable carrier frequency. 2.4 GHz to 2.525 GHz
- Configurable transmission power: 0, -6, -12, -18 dBm
- Automatic Retransmits (ART) after transmission failure
- Configurable number of retransmits: 0 to 15
- Configurable ART time-out delays: 250 μs to 4000 μs
- Master / Slave mode configuration
- Generation of ACK packets

All of these features can be activated and manipulated in the configuration file of the simulation. They can be changed without a re-compilation of the simulation software.

Each of the two modes of operation (PTX, PRX) needs a different MAC layer implementation. Figure 4a shows a simplified state diagram for the master device while Figure 4b shows the same for the slave. The master stays in the Standby mode until the RX mode is activated by a control message of the application layer. The receiver is activated after the end of the RX Settling phase. The device stays in this state until a message is received from the physical layer or it is disabled by a control message. If the generation of ACK packets is activated the TX is enabled for the ACK transmission, otherwise the transceiver switches back to RX. The slave device waits in Standby mode until a message arrives from the application layer. The message is transmitted after the end of the TX Settling phase. If the ACK packet generation is enabled in the network, the devices switches to RX to receive the master‘s ACK and starts the time-out counter. When an ACK packet is received within the ACK reception period the devices switches back to Standby. If no ACK is received the transmission is restarted until the maximum number of retransmission attempts is reached.

A main task of the MAC layer is to control the radio in the Physical Layer. The implementation determines when to trigger state switches and is responsible for handling physical layer control messages.

3) Application Layer: The application layer contains all high level algorithms that are usually part of the sensor node firmware. They define the way the radio is utilized for a given scenario. Here, the transmission of messages to other nodes is started or the transceiver is set to the *Power Down* state when no communication is necessary. One possible application is the evaluation of different sleep cycle strategies and their optimization with respect to the transceiver parameters.

The energy consumption of all application layer related operations is neglected in this energy model since this is not directly related to the radio operation.

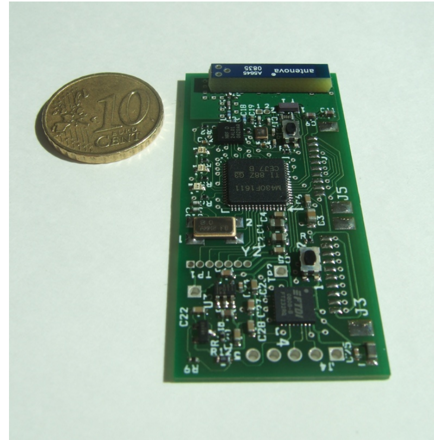


Figure 5. Prototype of the WBSN Hardware

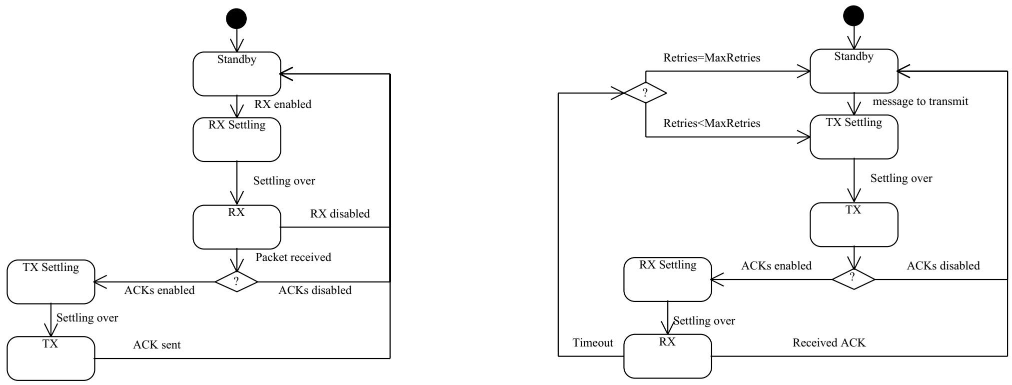
Our first application layer implementation demonstrated a periodic transmission of sensor data, a typical application scenario for medical sensors. This could be a SPO_2-Sensor, periodically sending the estimation of the oxygen saturation level to the network master. The number of payload bytes and the delay between two packets can be configured in the simulation setup (e.g. Sending a 15 Byte datagram every 100 ms).

4) Battery Module: Two different implementations can be used as *BatteryModule*. The first implementation is based on the OMNet++ module *SimpleBattery* [14] which is part of the MiXiM framework. This module uses a simple linear battery model representing a battery with a given capacity. Every transceiver operation reduces the remaining energy in the battery. A node stops all operation on battery depletion. This approach can be used to estimate the network lifetime for a given set of parameters.

The second implementation is a pure C++ module, not an OMNeT++ module. It only tracks the energy consumption of each radio state and reports the results after the simulation has stopped. This approach is sufficient for most experiments and significantly reduces the number of events that have to be processed by the simulation core, resulting in faster simulations.

IV. Simulation and Results

The energy model was used to prepare and optimize the firmware development for our medical sensor node hardware. We were able to simulate the influence of application layer design decisions to the energy efficiency of the medical system. The application layer algorithms can be used in the node firmware with minor changes since the simulation framework is written in C++. Figure 5 shows the prototype of a medical senor node consisting of a MSP430F1611 microcontroller, the nRF24L01 radio and other peripheral components.



(a) Master (PRX) (b) Slave (PTX)

Figure 4. Simplified State Diagrams of the MAC layer implementation

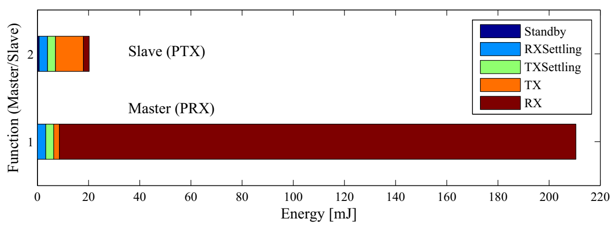


Figure 6. Energy Consumption of Master and Slave Devices

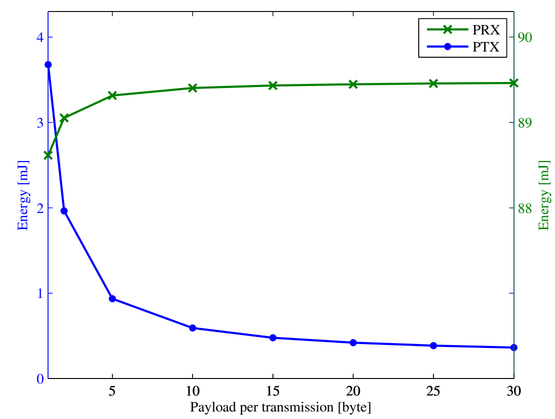


Figure 7. Energy consumption for different payload lengths

A. Energy Consumption of Master and Slave Devices

The first experiment simply compares the energy consumption of master and slave devices. The slave device (sensor) periodically transmits measurements. The master device receives data all the time and forwards it to the application. A message, containing 32 payload bytes, is transmitted every 10 ms at a data rate of 1 MBit/s and a transmission power of 0 dBm. The generation of acknowledgment packets is enabled and the simulation stops after 1000 messages. The resulting energy consumption is shown in Figure 6. The master device (1) consumes much more energy than a slave device (2). A huge part of the energy is consumed in the receiving state, which is enabled all the time when waiting for incoming packets. The slave consumes the most energy in the transmission state and a smaller part when waiting for the ACK packets. This experiment highlights the requirements for the master device. To maximize the network lifetime, this device needs a battery with a higher capacity than the sensor nodes, a permanent power supply (if applicable) or an adapted sleep cycle strategy.

B. Energy Consumption and Packet Overhead

Payload bytes are always embedded in a packet structure for transmission. The specific frame format of the nRF24L01 consists of bits for a preamble, the destination address, control information and CRC data. All these bits are necessary for the proper functioning of the protocol, but since they are no payload they are called packet overhead.

The second experiment examines the influence of packet overhead to the energy consumption. The first simulation run sends one payload byte every 5 ms, the next run sends two payload bytes every 10 ms and the last run 30 payload bytes every 150 ms. All other simulation parameters (2 CRC bytes, 5 address bytes, 1 MBit/s, 0 dBm, 3.0 V) were kept constant and every simulation run stopped at the same time. The simulation results, shown in Figure 7, illustrate the great impact of overhead bytes. For PTX devices, the energy consumption for transmitting data over a period of time can be drastically reduced by gathering payload before sending a frame. This comes at the cost of slightly increased power consumption for the PRX device. When more payload bytes are collected and thus fewer packets are transmitted, the Master stays in the RX state for a bigger fraction of the time. RX is the state with the highest energy consumption (see Tab. I). It is very inefficient to frequently send small packets. The best strategy to conserve energy is to collect as much

Table II
MEASURED CURRENT CONSUMPTIONS VS. SPECIFICATION

State	Specification [mA]	Measurement [mA]
TX Settling (0/-6/-12/-18 dBm)	8.0	7.7/6.5/5.7/5.4
RX Settling	8.4	6.4
RX (1/2 MBit/s)	11.8/12.3	11.9/12.3
TX (0/-6/-12/-18 dBm)	11.3/9.0/7.5/7.0	11.7/9.2/7.7/7.1

payload as possible before a transmission. This reduces energy cost for overhead bytes and for ACK packets that have to be transmitted in addition to each data packet. Such a strategy can have several drawbacks: Firstly, it can contradict the latency requirements of the application. Secondly, longer packets can be costly when bit error rates are high and packets have to be retransmitted. Our simulation model can be used to find a good trade-off between latency, quality-of-service and energy efficiency.

C. Measurements

Measurements of the radio's current consumption during operation were carried out using a 1.25 MSample/s USB data acquisition device and a measurement resistor. The 1-Ohm precision resistor was directly placed in the power supply line of the transceiver on our prototype hardware. The current consumption was calculated from a high resolution differential voltage measurement across the resistor and the known resistor value.

The results are shown in table II. 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.

The measured timings exactly matched the expected and simulated behavior.

V. CONCLUSION

In this paper, we presented a detailed simulation model of the ultra-low-power transceiver nRF24L01 for MiXiM. The model simulates the behavior and the energy consumption of the real hardware. The presented simulation model is a valuable tool for network designers and implementers when working with the nRF24L01. It can be used to evaluate different application strategies and analyze the performance of simple wireless networks in different configurations.

In the future, we would like to add the last missing features of the transceiver like FIFO handling, ACK payload and the second standby state. Further on, we plan to implement models of other transceiver chips for comparative experiments. The simulations in this paper use a very simple path loss model and fixed node positions. The following experiments will include a more realistic propagation and mobility model for WBSNs.

REFERENCES

[1] Nordic Semiconductor, "nrf24l01 single chip 2.4ghz transceiver: Product specification v2.0," July 2007. [Online]. Available: http://www.nordicsemi.no

[2] Texas Instruments, "Cc2420 - 2.4 ghz ieee 802.15.4 / zigbee-ready rf transceiver - product data sheet." [Online]. Available: http://focus.ti.com/lit/ds/symlink/cc2420.pdf

[3] MiXiM Project, "Mixim project web page." [Online]. Available: http://mixim.sourceforge.net

[4] OMNeT++ Community, "Omnet++ project web page." [Online]. Available: http://www.omnetpp.org

[5] C. Zhurong, H. Chao, L. Jingsheng, and L. Shoubin, "Protocol architecture for wireless body area network based on nrf24l01," in *Automation and Logistics, 2008. ICAL 2008. IEEE International Conference on*, 2008, pp. 3050–3054.

[6] S. S. Sonavane, V. Kumar, and B. P. Patil, "Designing wireless sensor network with low cost and low power," in *Networks, 2008. ICON 2008. 16th IEEE International Conference on*, 2008, pp. 1–5.

[7] Z. Dechun and P. Chenglin, "A small low-power reliable communication module in a wireless monitoring system," in *Bioinformatics and Biomedical Engineering, 2007. ICBBE 2007. The 1st International Conference on*, pp. 1194–1197.

[8] S. Pollin, M. Ergen, S. C. Ergen, B. Bougard, F. Catthoor, A. Bahai, and P. Varaiya, "Performance analysis of slotted carrier sense ieee 802.15.4 acknowledged uplink transmissions," *Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE*, pp. 1559–1564, 2008.

[9] F. Chen, I. Dietrich, R. German, and F. Dressler, "An energy model for simulation studies of wireless sensor networks using omnet++," *Praxis der Informationsverarbeitung und Kommunikation (PIK)*, vol. 32, no. 2, pp. 133–138, 2009.

[10] S. Kellner, M. Pink, D. Meier, and E. O. Blass, "Towards a realistic energy model for wireless sensor networks," in *Wireless on Demand Network Systems and Services. Fifth Annual Conference on*, 2008, pp. 97–100.

[11] A. Köpke, M. Swigulski, K. Wessel, D. Willkomm, P. T. K. Haneveld, T. E. V. Parker, O. W. Visser, H. S. Lichte, and S. Valentin, "Simulating wireless and mobile networks in omnet++ the mixim vision," in *Simutools '08: Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops*, ICST, Brussels, Belgium, 2008, pp. 1–8.

[12] K. Wessel, M. Swigulski, A. Köpke, and D. Willkomm, "Mixim: the physical layer an architecture overview," in *Simutools '09: Proceedings of the 2nd International Conference on Simulation Tools and Techniques*, ICST, Brussels, Belgium, 2009, pp. 1–8.

[13] Anna Förster, "Batterymodule 2.0." [Online]. Available: http://www.inf.usi.ch/postdoc/foerster/downloads.html

[14] Laura Marie Feeney, "Energy framework v0.9." [Online]. Available: http://www.sics.se/~lmfeeney/software/energyframework.html