Transmit Power Adaptation for Optimizing Energy Consumption in WBANs

Master Thesis

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Packet reception rate (PRR) and energy consumption are two important metrics when designing a wireless body area network (WBAN). Due to posture changes and influences from the environment, the wireless links in WBANs have a relatively low quality that varies over time. Due to the limited size of wireless body sensors and their power supply, energy consumption should be as small as possible. This thesis presents a study about power adaptation techniques for WBANs and gives an implementation of a reliable and robust transmit power adaptation mechanism. It aims to optimize the energy consumption of the entire WBAN while ensuring PRR requirements. Experiments with nodes placed on a human body are done and the results are used in further simulations to test and verify the quality and performance of the designed mechanism. The transmit power adaptation mechanism presented in this thesis ensures PRR application requirements for different postures at the cost of at most 10% extra energy compared to the optimal configuration.
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1 Introduction

This thesis covers the work carried out during my master project. The main goal of the project was designing a reliable transmit power adaptation mechanism that tries to optimize the energy spent in the wireless body area network (WBAN) while aiming at a predefined packet reception ratio (PRR).

1.1 Wireless body area networks

A WBAN consists of tiny wireless sensor devices, called nodes, deployed at several positions on a human body, as illustrated by Figure 1. Each sensor is designed to measure a type of biological signal. Depending on the application, a sensor device can (pre)process the raw data or transmit it directly to a gateway node that is used to transmit the data to an observer. This observer, a computer of the doctor or trainer for example, can be connected directly or via a peripheral network. The gateway acts as a bridge between the WBAN sensor nodes and observer and can have a larger power supply.

Figure 1: Example WBAN setup

WBANs are in many ways similar to wireless sensor networks (WSNs), but with important differences. While WSNs often consist of homogeneous sensors, WBANs have typically heterogeneous sensors with a broad range of sampling periods and requirements. The size of a WBAN is typically smaller than the size of a WSN, where the first one covers a human body. The latter could cover an entire building, campus or even a city. The fact that wireless body sensors are placed on a human body limits their size, weight and thus energy constraints. The energy sources for these tiny sensors are also very limited. Instead of wearable sensors one could also think about implantable sensors which have even tighter energy constraints.

Another characteristic of a WBAN is the low quality wireless link that varies over time. The human body strongly attenuates RF signals while posture changes and frequent body movements make the environment for wireless communication even worse. Figure 2 shows an example of the PRR of a sensor node with constant transmit power level where the subject does not move. The link quality of this node varies from high quality to low quality over time. This shows that wireless links in WBANs are affected by their RF environment or small body movements and transmitting on a fixed power level requires more energy than needed. Ex-
Experiments show that nodes can have low quality links at different transmit power levels. Different environments can also lead to different results. Transmit power adaptation is thus necessary for WBANs. Due to the tight energy constraints optimizing energy consumption in WBANs is important.

![Figure 2: Low quality and time-varying link](image)

1.2 Application domains

Healthcare is the major domain where one could use wireless sensor nodes. Patients may be equipped with sensors to monitor some body signals such as heart rate (ECG), blood oxygen levels (SpO2) and body temperature. These examples are only a small subset of the number of biological signals that are measured in healthcare environments. It is clear that measuring the electrical activity of the heart (ECG) requires a different sensor than a temperature sensor, with respect to sampling rate, accuracy and amount of data that needs to be transferred [1].

One of the problems in research for healthcare is the lack of methods to easily collect large data sets from people suffering a particular disease [16]. The World Health Organization concludes in their report that treatment of global diseases cannot be achieved without evidence from research. WBANs make it easier to collect data from patients without degrading mobility of the patient or even the need to let the patient stay inside a hospital.

Besides health and personal care, sports is another domain that would benefit from using wireless sensors to monitor biological signals of the human body. One could think of athletes where it would be possible to track precise movement and placement of their legs and body parts while training. Medical information like heart rate and blood oxygen levels could also be measured and analyzed by their trainers.

The results of this master project can contribute to future development of sensor technologies in all these domains. When WBANs advance, more people can be monitored during daily life and diagnoses from medical personnel and
sport trainers can be based upon a wider set of results instead of results of a single measurement. Early measurements and detection of abnormal (biological) signals could lead to less mortality due to late detection of for example symptoms of cardiovascular diseases. Another aspect is that life of people with chronic diseases would be more comfortable when the sensors they need to wear become smaller and do not obstruct mobility in their daily life.

1.3 Contribution

Reliable end-to-end links are required to transmit important signals of vital body organs through a WBAN. Power consumption should be minimized to meet the tight constraints that follow from the dimensions of a sensor node and its power source (i.e., battery). This is even more important when going to smaller scale like implantable devices. Some kind of controller is needed in order to guarantee reliable data delivery from the sensor nodes to a monitor application over the time-varying wireless links in order to be robust against dynamics such as posture changes, mobility, and environmental changes.

![Figure 3: Overlapping radio area multiple WBANs. Lowering transmit power for WBAN 1 from $T_x = T'_x$ to $T_x = T''_x$ avoids overlap.](image)

When using multiple WBANs on short distance the interference should be minimized. The communication from a WBAN should ideally not interfere with other WBANs. In Figure 3 the overlapping area of two transmit radios is marked, which should be as small as possible to minimize interference. To avoid interference, WBAN nodes should be able to adapt their transmit power. Interference is an error source that effects the PRR and will be considered implicitly since the control mechanism responds on the PRR.

In this thesis a WBAN in star configuration is considered with one node acting as gateway. Each node has a single-hop link to the gateway and multiple transmit power levels. The MyriaNed nodes used have four different power levels, but the proposed transmit power adaptation mechanism can also be applied on different number of power levels. A global control mechanism is used and implemented in the more powerful gateway node. An experiment is done to find the optimal location of the gateway.

This thesis proposes a reliable transmit power adaptation mechanism that optimizes power consumption while aiming at a predefined PRR.
1.4 Thesis overview

Section 2 reviews related work on power optimization and adaptation techniques for WBANs. Section 3 describes the problem statement for this master project. The specification of the hardware used during experiments is given in Section 4 and in Section 5 an overview is given of ways to monitor a WBAN. The proposed transmit power adaptation mechanism is explained in Section 6. The experiments carried out are explained in Section 7. The results of the experiments and a possible solution to the problem is given in Section 8. An overall conclusion is given in Section 9 and recommendations for future research are given in Section 10.
2 Related work

The radio of a WBAN usually consumes orders of magnitude more energy than the data processing part [20]. For a radio, the amount of energy required to communicate increases with the distance and obstructions of the radio signal. The experiments of Natarajan et al. [14] show that the decision of an appropriate network architecture highly depends on the environment and the demands of an application. This conclusion is in line with the experiments done during this project and underlines the importance of a power control mechanism for WBANs.

Liang et al. [7] have presented a routing strategy for multi-hop WBANs based on adaptive power control. Their protocol is based on CTP [5] and aims to minimize the expected transmissions for a path from a source node to the gateway. A key difference with the work in this thesis is that the protocol designed by [7] needs to have knowledge about the network topology and link properties. Posture changes and environmental influence leads to time-varying quality of links in WBANs and make this adaptive routing strategy less robust.

The protocol presented by Nabi et al. [10] is robust against frequent changes in the network topology which are typical in WBANs. The routing protocol does not make any assumptions about the position of the nodes or the link properties. The transmit power adaptation protocol presented in [10] aims at providing a proper link from every node (possibly via multi-hop) to the gateway node. An inlink and outlink quality for each node is computed, which are derived from the packet reception of neighboring nodes. The proposed protocol is however not optimized for energy consumption as packets are always being forwarded by the nodes and taking multiple hops might be worse than increasing transmit power for a particular node. A hybrid approach is presented in [11] where nodes change from star topology to multi-hop topology when a link connection is insufficient. However, a fixed power level for all nodes is used per experiment. A more energy efficient solution is presented in this thesis where each node is optimized for minimizing energy.

Smith et al. [19] present a transmit power control based on channel prediction. This mechanism uses characteristics of the channel, that needs to be measured upfront. Scaling factors are derived from some experiments, which are used to increase or decrease power levels. Their objective was to find a reliable transmit power control that uses channel prediction. The mechanism in [19] assumes a minimum receiver sensitivity at four different data rates that needs to be satisfied. The control mechanism presented in this thesis does not need any information about the link quality of the wireless channels at design-time. The transmit power control mechanism of [19] needs to be changed according to the hardware used or even when used in a different environment than where channel measurements were done, making it less robust than the controller presented in this thesis. The topology in [19] with multiple receivers is also different from the topology considered in this thesis with a single receiver (gateway).

The transmit power adaptation mechanism presented in this thesis can be used in every environment or application and does not make any assumptions about them. This makes this mechanism more robust when compared to existing power adaptation techniques. Hardware independence is another difference with existing power adaptation mechanisms. The proposed mechanism works independent of the number of power levels.
3 Problem statement

A WBAN can be defined by a set of $N \in \mathbb{N}$ nodes $S$ attached to a human body, as given in Equation 1. A WBAN thus consists of $N-1$ sensor nodes and 1 gateway node, with the gateway node $s_g \in S$. Data from all sensor nodes is supposed to be delivered to the gateway node.

$$S = \{s_1, s_2, \ldots, s_N\}$$  \hspace{1cm} (1)

Each sensor node has $P \in \mathbb{N}$ distinct transmit power levels where $pl_x < pl_y$ if $x < y$:

$$\text{power levels} = \{pl_1, pl_2, \ldots, pl_P\}$$  \hspace{1cm} (2)

The relation between transmit energy consumption and transmit power level is a function of the transmit power level, where $E_i(x) < E_i(y)$ if $x < y$. It means that increasing the power level for a node results in using more energy for that node.

$$E_i(x) = F(pl_x)$$  \hspace{1cm} (3)

The total energy consumption of the radio from a WBAN node consists of the transmit, receive and idle energy. As explained in Section 4.3, we only consider the transmit energy. The total transmit energy consumption of the WBAN is defined as the sum of the transmit energy of all nodes except the gateway. Energy optimization for the gateway is less critical and not part of this project, as explained in Section 1. A higher transmit energy is directly related to the power source needed for a WBAN and transmit energy should thus be minimized when possible.

$$E_{\text{transmit}} = \sum_{i=1}^{N} E_i \quad \text{for all } s_i \neq s_g$$  \hspace{1cm} (4)

Let $L_{i,j}^\tau$ represent the link packet reception status of node $s_i$ at TDMA round $\tau$ as a logical signal (0 or 1) with $L_{i,j}^\tau = 0$ representing no connection and $L_{i,j}^\tau = 1$ meaning there is a connection between node $s_i$ and $s_j$ at sample-time $\tau$. A window-based computation is used to calculate the PRR for a limited time interval. The window length is defined by $W$. From the link packet reception status the PRR of node $s_i$ at time $\tau$ at node $s_j$ is defined as shown in Equation 5.

$$\text{PRR}_{i,j}^\tau(W) = \frac{1}{W} \sum_{k=0}^{W-1} L_{i,j}^{\tau-k}$$  \hspace{1cm} (5)

In the following equations node $s_j$ will be omitted when the gateway node is known and single-hop transmissions are used. The PRR at time $\tau$ with window length $W$ for node $s_i$ received at the gateway is then denoted as $\text{PRR}_i^\tau(W)$.

An important difference for reliability in WBANs that is not visible from the PRR is the situation shown in Figure 4. With a window length $W = 12$ the PRR for both situations is equal to 75%. Using a window length of $W = 4$ the PRR is different for each case (75% vs. 50%). For most practical applications the case in Figure 4(b) is worse than Figure 4(a) because multiple adjacent messages are lost. This problem should be considered when selecting the appropriate window length.
From application point of view the WBAN has to satisfy the PRR requirement given by Equation 6 after a certain amount of time. In an optimal situation all sensor nodes in $S$ should meet the requirement. During evaluation of the transmit power adaptation mechanism, 200 samples are used to calculate the PRR with a window size $W = 10$.

$$PRR_i^\tau(W) \geq PRR_{req}$$  \hspace{1cm} (6)$$

During the experiments, which will be explained in Section 7, time-varying behavior of some nodes was visible explicitly. Figure 5 shows the PRR(10) of node $s_8$ measured at the gateway during a 5 minute experiment. The first 1250 samples the PRR is almost 100%. In the last part of the experiment the PRR suddenly drops. The subject was sitting on a chair without moving. Most likely the environmental conditions changed during the experiment that caused interference with the WBAN nodes. This experiment shows that transmit power for WBANs cannot be calculated offline but need to be calculated online to deal with the time variability of the wireless links.
The aim of the transmit power adaptation mechanism presented in this thesis is to minimize the transmit energy $E_{\text{transmit}}$ needed if the application requirement from Equation 6 is satisfied to save scarce battery resources.
4 Hardware setup

4.1 MyriaNed nodes

To evaluate the protocol proposed in this thesis, MyriaNed [3] nodes are used. These wireless nodes feature an ATMEGA128 microcontroller and a Nordic nRF24L01 radio chip [18]. The radio chip works in the license free 2.4 GHz ISM band and uses a data rate of 2 Mbps. The four distinct transmit power levels and transmit currents are given in Table 1 while the receive current is $I_{\text{receive}} = 12 \, mA$. The idle current of the radio chip is only $I_{\text{idle}} = 22 \, \mu A$. Each MyriaNed node has a 4 Megabyte flash memory which can be used to log data during experiments. Figure 6 shows a single MyriaNed node with its components.

<table>
<thead>
<tr>
<th>reference</th>
<th>power level (dBm)</th>
<th>$I_{\text{transmit}}$ (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL1</td>
<td>-18</td>
<td>7.0</td>
</tr>
<tr>
<td>PL2</td>
<td>-12</td>
<td>7.5</td>
</tr>
<tr>
<td>PL3</td>
<td>-6</td>
<td>9.0</td>
</tr>
<tr>
<td>PL4</td>
<td>0</td>
<td>11.3</td>
</tr>
</tbody>
</table>

The MyriaNed nodes are chosen due to availability at the Electronic Systems group from the Eindhoven University of Technology. The transmit power adaptation mechanism proposed in this thesis can also be used for other WBAN nodes that provide possible a different number of power levels.
4.2 Protocol stack

The MyriaNed nodes use a collision-free TDMA-based MAC protocol based on gMAC [6]. In this TDMA-based protocol, fixed-size TDMA frames are used and divided into fixed time slots used for communication. We use a simple fixed slot assignment for slot scheduling mechanism; every node transmits in a fixed time slot of the TDMA frame. The nodes are configured such that each node transmits at every TDMA frame. When a node does not communicate it goes into a low energy idle mode. Guard time is inserted at the beginning and end of each slot to avoid problems due to time synchronization. Relevant parameters for the TDMA-based protocol are given in Table 2. With 16 active slots per TDMA frame, the duty cycle is as low as 1.2%.

<table>
<thead>
<tr>
<th>reference</th>
<th>value</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{frame}}$</td>
<td>0.1 – 1 s</td>
<td>TDMA frame length</td>
</tr>
<tr>
<td>$T_{\text{slot}}$</td>
<td>764 µs</td>
<td>TDMA slot length</td>
</tr>
<tr>
<td>$T_{\text{transmit}}$</td>
<td>164 µs</td>
<td>transmission time</td>
</tr>
<tr>
<td>$T_{\text{guard}}$</td>
<td>300 µs</td>
<td>guard time</td>
</tr>
</tbody>
</table>

4.3 Energy consumption

The energy consumption for each frame is identical for the MyriaNed nodes due to the TDMA-based communication mechanism. The radio energy per node is calculated per frame according to Equation 7 and consists of the energy consumed during transmit, receive and idle mode.

$$E_{\text{radio}} = E_{\text{transmit}} + E_{\text{receive}} + E_{\text{idle}}$$  \hspace{1cm} (7)

The transmit energy consists of the energy for transmission and the energy needed for transition to the transmit mode. The transmit energy per frame is equal to the transmit energy of one slot as there is only one active slot per TDMA frame per node. $I_{\text{switch}}$ is the average radio current during switching to transmit mode and $T_{\text{switch}}$ the switch time needed in the nRF24L01 radio chip.

$$E_{\text{transmit}} = (I_{\text{transmit}} \times T_{\text{transmit}} + I_{\text{switch}} \times T_{\text{switch}}) \times V_{\text{bat}}$$  \hspace{1cm} (8)

The receive energy depends on the number of slots a node listens to ($N_{\text{listen}}$).

$$E_{\text{receive}} = [I_{\text{receive}} \times (T_{\text{transmit}} + 2 \times T_{\text{guard}})] \times V_{\text{bat}} \times N_{\text{listen}}$$  \hspace{1cm} (9)

In the above equation the slot time $T_{\text{slot}} = T_{\text{transmit}} + 2 \times T_{\text{guard}}$ as explained in Section 4.2. The idle energy depends on the time there are no active slots and is given by Equation 10:
\[ E_{\text{idle}} = I_{\text{idle}} \times (T_{\text{frame}} - T_{\text{slot}} \times N_{\text{active}}) \times V_{\text{bat}} \]  \hspace{1cm} (10)

Table 3: Parameters power supply

<table>
<thead>
<tr>
<th>reference</th>
<th>value</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_{\text{transmit}})</td>
<td>7.0 – 11.3 mA</td>
<td>transmit current (Table 1)</td>
</tr>
<tr>
<td>(I_{\text{receive}})</td>
<td>12.3 mA</td>
<td>receive current</td>
</tr>
<tr>
<td>(I_{\text{idle}})</td>
<td>22 (\mu) A</td>
<td>idle current</td>
</tr>
<tr>
<td>(I_{\text{switch}})</td>
<td>8 mA</td>
<td>avg. current switching to transmit mode</td>
</tr>
<tr>
<td>(T_{\text{switch}})</td>
<td>130 (\mu)s</td>
<td>radio mode switch time</td>
</tr>
<tr>
<td>(V_{\text{bat}})</td>
<td>2.4 V</td>
<td>battery voltage</td>
</tr>
<tr>
<td>(N_{\text{listen}})</td>
<td>1</td>
<td>number of slots a node listens</td>
</tr>
<tr>
<td>(N_{\text{active}})</td>
<td>2</td>
<td>number of active slots</td>
</tr>
</tbody>
</table>

With the numbers from Table 2 and Table 3 and Equations 7-10 the transmit energy can be calculated and is \(E_{\text{transmit}} = 5\ \mu\)J per TDMA frame for the lowest and \(E_{\text{transmit}} = 7\ \mu\)J per TDMA frame for the highest power level. The receive energy \(E_{\text{receive}} = 23\ \mu\)J per TDMA frame and the idle energy for one TDMA frame is \(E_{\text{idle}} = 53\ \mu\)J. As stated before, there is only one transmission per TDMA frame.
5 Online WBAN observation tool

5.1 Observation setup

During research and development a WBAN needs a monitor tool to analyze the network behavior and performance. The MyriaNed nodes, described in Section 4, have the ability to write data to a flash memory. It may also be useful to view the performance of the network online, during experiments, instead of downloading the log files after each experiment. In order to be able to capture live data from the WBAN, a laptop or computer can be used which is connected to the WBAN via an extra node that is called ‘control node’. A typical setup is shown in Figure 7 where the gateway communicates with a control node that is attached to a laptop. The control node and the laptop are not part of the WBAN, but are used to capture data from the network.

Software for Microsoft Windows is available [12] and can be used to visualize WBAN metrics. Via a Graphical User Interface (GUI) parameters like transmit power level and sampling period can be set and are sent to the WBAN via the control node. After configuration of the network, the control node has no influence on the performance and behavior of the network. Several plots show the performance metrics of the WBAN like energy consumption and PRR. The GUI also shows the state of each node, whether it is connected to the gateway.

In the current implementation of this tool, the gateway and control node need to have a (wireless) link in order to capture live data. This wireless link hampers the mobility of the person wearing the WBAN and thus limits the experiments that can be done. To increase mobility a handheld device like a smartphone could be used. It might also be possible to remove the control node as shown in Figure 8.

The Samsung Galaxy SII i9100 [17] is chosen as the handheld device because of availability at the Electronic Systems group at the Eindhoven University of Technology. This Samsung smartphone runs Android 4.1.2 and has various connectivity possibilities like USB, Bluetooth and WiFi (Table 4).

The MyriaNed control node has an USB 2.0 connector and acts as a USB device. The Windows GUI application visualizes the configuration of each node. A similar application can be made for Android to visualize network status on a mobile phone. Using USB 2.0 would possibly simplify the connection and does not need any modification on control node and gateway. Disadvantages are that still the extra control node is needed and it should be connected by physical wires.
The MyriaNed USB connection is made with a serial-to-USB converter. The data transferred via USB is also directly available via the (UART) connectors for sensor boards (Figure 6). As alternative to USB, Secure Digital Input Output (SDIO) can be used to connect the smartphone to the control node. As with USB, the connection is still physical by means of wires.

Near field communication (NFC) is a wireless technique that works on a different frequency than the MyriaNed nodes and would not interfere. The limited distance that can be reached (a couple of centimeters) makes NFC not suitable for monitoring the behavior of a WBAN.

Bluetooth and WiFi both work at the 2.4 GHz band but cannot be connected directly with the MyriaNed nodes. Bluetooth consumes less power than WiFi and low-cost modules like the Roving Networks RN-42 Bluetooth SMD module [15] are available and can be connected to the MyriaNed board. Starting at Android 4.3, Bluetooth Low Energy is available that consumes even less energy (factor 2-10 less than classic Bluetooth).

### 5.2 Proposed solution

If the control node can be connected via USB 2.0 to the Android smartphone, no changes in the MyriaNed configuration would be necessary. The software of [12] could be ported to Android and the smartphone can replace the laptop.
The Android smartphone is able to act as USB host but did not recognize the MyriaNed device which has a serial-to-USB transceiver to communicate over USB. The FT2232D serial-to-USB transceiver [4] is supported by an open source USB-to-serial library for Android but was also not able to communicate with the MyriaNed node. This is due to custom firmware of the serial-to-USB transceiver from the MyriaNed nodes.

With a third party Bluetooth module it is possible to communicate with the MyriaNed node via Bluetooth. The Roving Networks RN-42 Bluetooth Module [15] is proposed because of low price and direct availability. The RN-42 is a small form factor, low power, Bluetooth radio with antenna with an UART interface that can be directly connected to the UART of the gateway. The gateway should be modified such that data originally sent to the control node is now published via the UART. Android does support Bluetooth without additional third party libraries.

Figure 9 shows the setup with the Bluetooth module attached to the gateway node. The two LEDs indicate the status of the Bluetooth module and the push button can be used to reset the module. The smartphone can discover devices and connect with the Bluetooth module. When the two devices are successfully paired, data can be exchanged. The deadline for this master project prevented to finish the actual communication between gateway and smartphone, but tests showed that communication via Bluetooth is relatively easy to setup with an external module attached to the gateway.

![Figure 9: Experimental Bluetooth setup](image)

Figure 10 shows the electrical schematic of the proposed solution. Output PIO5 is used to drive a LED that indicates the connection status. If the LED is on, the device is connected via Bluetooth. A connection is possible when the LED blinks once a second, which means the boot cycle is completed. A 100 nF ceramic ca-
Capacitor is used to decouple the power supply. When the battery on the MyriaNed board cannot provide a stable 3.0 V - 3.3 V supply, an external power source should be used. Communication is not reliable with an unstable power supply, but this is not visible at first sight because the LED indicator does work as expected.

It is possible to connect $UART_{TX}$ directly to $UART_{RX}$ and create a loopback to test communication between the Android smartphone and the Bluetooth module.

![Figure 10: Electrical schematic for minimal setup](image-url)
6 Transmit power adaptation mechanism

6.1 Controller model

The transmit power adaptation mechanism, performed by the gateway as central controller, has to find an optimal configuration for the power levels of all nodes in the WBAN. It receives packets from the sensor nodes and sends back a desired power level to each sensor node. This can be modelled as shown in Figure 11 where the transmit power adaptation mechanism is the controller and the sensor nodes are modelled as environment. A third entity called observer is used to observe the behavior of the sensor nodes and the controller. It is used for development purposes and will not be present in a real application.

![Figure 11: System overview](image)

On application level a required PRR (PRR_{req}, Equation 6) is given. The posture is given by the environment. The controller aims to compute the power level for each node, based on the PRR that is calculated from the number of received messages. Note that the controller is unaware of the posture. In the model the PRR is given by the environment and the gateway can compute the PRR of each link.

6.2 Proposed mechanism

A transmit power adaptation mechanism is developed where transmit power for a node is increased when the PRR requirement is not met and decreased when the PRR requirement is met. A delay value $Delay_i$ is used to prevent hopping from the lowest to the highest power level without measuring the effect of the power levels that are in between $pl_0$ and $pl_P$. This value is used to minimize the effect of the non-monotonic relation of power level and link quality that is observed at some nodes and explained in Section 8.3. The initial value of $Delay_i$ is based on experiments. A performance evaluation of the proposed transmit power adaptation mechanism is given in Section 8.

Pseudocode of the proposed mechanism is given in Algorithm 1. The required PRR is given on application level. The window size $W$ is empirically obtained, with a sample rate of 1 s. The time over which the PRR is calculated is 10 s in this case. If this window is too long, changes of wireless links that are not
relevant anymore are taken into account. A too short window leads to unstable, fluctuating, values. During the experiments parameters were assigned values as given in Table 5.

**Algorithm 1** Transmit Power Adaptation Mechanism

```
1: for each \( s_i \in S \setminus s_g \) do
2:   if \( Delay_i = 0 \) then
3:     if \( PRR_i > PRR_{req} \) then
4:       \( pl_i^{\tau+1} \leftarrow \max(pl_1, pl_i^{\tau-1}) \)
5:     else
6:       \( pl_i^{\tau+1} \leftarrow \min(pl_P, pl_i^{\tau+1}) \)
7:     \( Delay_i \leftarrow Delay \)
8:   end if
9: end if
10: if \( Delay_i > 0 \) then
11:   \( Delay_i \leftarrow Delay_i - 1 \)
12: end if
13: end for
```

**Table 5**: Initial parameter values

<table>
<thead>
<tr>
<th>reference</th>
<th>value</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( PRR_{req} )</td>
<td>90%</td>
<td>minimum required PRR</td>
</tr>
<tr>
<td>( W )</td>
<td>10 samples</td>
<td>window size</td>
</tr>
<tr>
<td>( Guard )</td>
<td>2%</td>
<td>guard value</td>
</tr>
<tr>
<td>( Delay )</td>
<td>3 samples</td>
<td>delay after power increase</td>
</tr>
<tr>
<td>( pl_i^0 )</td>
<td>( pl_0 )</td>
<td>initial power level</td>
</tr>
</tbody>
</table>
7 Experiments

The experiments done during this project consist of physical experiments (Section 7.1) and simulations with data extracted from these experiments (Section 7.2). In the following sections we refer to the six different postures that are tested and shown in Table 6 and to the four different power levels of the MyriaNed nodes (Table 1).

Table 6: Postures considered in the experiments

<table>
<thead>
<tr>
<th>Reference</th>
<th>Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Sitting on a chair</td>
</tr>
<tr>
<td>P2</td>
<td>Sitting on the ground</td>
</tr>
<tr>
<td>P3</td>
<td>Standing</td>
</tr>
<tr>
<td>P4</td>
<td>Walking</td>
</tr>
<tr>
<td>P5</td>
<td>Lying down</td>
</tr>
<tr>
<td>P6</td>
<td>Running</td>
</tr>
</tbody>
</table>

The WBAN nodes were configured to send one message every TDMA round so that message reception and PRR could easily be calculated at the gateway. This data is extracted from the flash memory after every experiment and further processed.

7.1 Physical experiments

Extensive experiments were carried out by Nabi et al. [13]. During those experiments, 16 MyriaNed nodes were attached to a human body (Figure 12(b)) without a gateway: Each node sends data to all other nodes. The receiving node measures and logs the link packet reception status of every sending node at every TDMA round. In every experiment, all WBAN nodes were configured at one uniform power level and one posture was considered. Each experiment recorded 5 minutes of data with a sample rate of 10 samples per second, leading to $5 \cdot 60 \cdot 10 = 3,000$ samples per node per experiment.

A second series of experiments was carried out during this master project with a smaller set of MyriaNed nodes as shown in Figure 12(a). These experiments were done to analyze performance of the WBAN in different environments with and without interfering signals at the 2.4 GHz band. Each experiment recorded 300 samples of data with a sample rate of 1 sample per second. Only posture P4 (Walking) is considered. With these experiments, the time-varying characteristic of the WBAN was tested by doing the same experiment on different times of the day and in different locations (work environment and home environment). Tests done in the home environment showed more interference from probably other transmitters. The results of the experiments also show that repeating an experiment can lead to different outcomes depending on the location and presence of interfering signals. Compared to the results from the experiments with 16 nodes nodes at the
same location on the body perform different in both experiments. Even with no interference the exact position of the antennas does influence the link quality.

Figure 12: Node placement (images from [13], modified)

Figure 13 shows the PRR ($W = 10$) for different power levels for posture P4 (Walking). At the highest power level (0dBm) the PRR is almost 100% where at the lowest power level (-18dBm) the PRR fluctuates between 30% and 90%. The PRR of node $s_1$ is slightly less than the PRR of node $s_2$, but both follow the same trend. The average PRR per power level per node is given in Table 7. This experiment shows the variation of PRR between the power levels for each node. Node $s_1$ (lower leg) has a PRR in the range 53% - 100% while node $s_4$ (hand) has an average PRR of 73% at the lowest power level and 96.5% at the highest power level. Node $s_2$ outperforms node $s_4$ on power levels 1, 2 and 3 but node $s_4$ has a higher PRR on the lowest power level.

Table 7: Average PRR per power level (Posture P4)

<table>
<thead>
<tr>
<th>power level</th>
<th>node $s_1$</th>
<th>node $s_2$</th>
<th>node $s_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
<td>96.5</td>
</tr>
<tr>
<td>2</td>
<td>93</td>
<td>96.5</td>
<td>89.5</td>
</tr>
<tr>
<td>3</td>
<td>69.5</td>
<td>73</td>
<td>79.5</td>
</tr>
<tr>
<td>4</td>
<td>53</td>
<td>63</td>
<td>73</td>
</tr>
</tbody>
</table>
Figure 13: PRRs for each power level (Posture P4)
7.2 Simulation model

The data collected from the experiments with 16 nodes (Figure 12(b)) can be used to simulate the behavior of the WBAN. From the link packet reception status $L_i^\tau$, the PRR can be calculated (Equation 5). A statistical distribution is computed with Matlab for every posture and power level which can be used to predict PRR ($\hat{PRR}$) for a given posture and power level. This distribution can be modelled as the environment in which the WBAN operates (Equation 11).

\[
\hat{PRR} = \text{environment}(\text{posture, power level})
\]  

(11)

For a given posture, the transmit power adaptation mechanism can acquire the predicted PRR and compute a power level for each node based on the predicted PRR:

\[
\text{power levels} = \text{controller}(\hat{PRR})
\]  

(12)

Various simulations are done to analyze the behavior of the proposed transmit power adaptation mechanism. Results of those simulations are presented in Section 8.

7.3 Gateway location

The transmit power adaptation mechanism is performed by the gateway node. As the link quality drops when the link distance increases, it is expected that the gateway should be placed central to the other nodes. The influence of the position of the gateway is simulated with the data available from the experiment with 16 nodes. The results, given in Figure 14, show the PRR ($W = 3000$), and the average and maximum size of burst packet loss for all nodes. Table 8 shows the results for node $s_7$ and $s_{13}$ in detail, which have the best results overall. This simulation reveals that node $s_7$ performs the best as gateway. The maximum and average burst size decrease for node $s_7$ when increasing power of all other nodes. For node $s_4$ the third power level leads to better results on burst size than the highest power level. The location of node $s_7$ has also a more practical value than the location of node $s_{13}$. The gateway is typically a larger node (larger battery) and can be attached to a belt or pants.
Figure 14: PRR and burst size for different gateways and 4 power levels
Table 8: PRR and burst size for $s_7$ and $s_{13}$ as gateway

<table>
<thead>
<tr>
<th>metric</th>
<th>power level</th>
<th>node $s_7$</th>
<th>node $s_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PRR</strong></td>
<td>1</td>
<td>50</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>83</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>95</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>97</td>
<td>96</td>
</tr>
<tr>
<td><strong>max. burst size</strong></td>
<td>1</td>
<td>2623</td>
<td>2195</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>838</td>
<td>2970</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>631</td>
<td>359</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>252</td>
<td>1924</td>
</tr>
<tr>
<td><strong>avg. burst size</strong></td>
<td>1</td>
<td>169</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>43</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>11</td>
<td>27</td>
</tr>
</tbody>
</table>
8 Performance evaluation

This section evaluates the performance of the proposed transmit power adaptation mechanism. This section first describes the design-time search for a benchmark configuration and then compares the performance of the transmit power adaptation mechanism with the near-optimal configurations found. Next an important behavior of the wireless links is explained. This section ends with a brief discussion why PRR is chosen as link quality estimation technique.

8.1 Design-time search for near-optimal power settings

To evaluate the performance of the proposed transmit power adaptation mechanism with the provided hardware, several metrics are compared to the optimal configuration of the WBAN. The optimal configuration of the WBAN is computed by an exhaustive search. The size of the WBAN prevents to traverse the entire design space which consists of 15 sensor nodes, 4 power levels and 6 postures. For each posture there are $4^{15} = 1,073,741,824$ possible configurations of power levels for each TDMA frame.

To minimize the design space and save computation time, a guided search is used instead of brute-force search. From the experiments we can extract the minimal PRR a node would achieve at a certain power level and given posture. With a PRR requirement of 90% we can safely ignore all power levels where a node does not reach a PRR of 60%. The minimized design space is given in Table 10 and consists of only $1^6 + 2^7 + 3^2 = 138$ configurations for posture $P_1$, for example. For postures $P_2$ till $P_6$ there are 20, 276, 308, 20, 858 configurations respectively, which adds up to a design space size of 1620 possible configurations. For each configuration the average energy per node and the average PRR of all nodes is calculated and shown in Figure 15. The minimum energy required per frame per posture for a PRR of at least 90% is given in Table 9.

Table 9: Minimum required energy per posture

<table>
<thead>
<tr>
<th>posture</th>
<th>energy (µJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>5.34</td>
</tr>
<tr>
<td>P2</td>
<td>5.46</td>
</tr>
<tr>
<td>P3</td>
<td>5.43</td>
</tr>
<tr>
<td>P4</td>
<td>5.71</td>
</tr>
<tr>
<td>P5</td>
<td>5.46</td>
</tr>
<tr>
<td>P6</td>
<td>5.70</td>
</tr>
</tbody>
</table>
Table 10: Minimized design space

<table>
<thead>
<tr>
<th>node</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1</td>
<td>pl₁, pl₂</td>
<td>pl₂</td>
<td>pl₁, pl₂</td>
<td>pl₁, pl₂</td>
<td>pl₁</td>
<td>pl₁, pl₂</td>
</tr>
<tr>
<td>s2</td>
<td>pl₁, pl₂</td>
<td>pl₂</td>
<td>pl₂</td>
<td>pl₂, pl₃</td>
<td>pl₁</td>
<td>pl₂, pl₃</td>
</tr>
<tr>
<td>s3</td>
<td>pl₂</td>
<td>pl₂</td>
<td>pl₂, pl₃</td>
<td>pl₃, pl₄</td>
<td>pl₂, pl₃</td>
<td>pl₂, pl₃, pl₄</td>
</tr>
<tr>
<td>s4</td>
<td>pl₁, pl₂</td>
<td>pl₁, pl₂</td>
<td>pl₂, pl₃, pl₄</td>
<td>pl₃, pl₄</td>
<td>pl₂</td>
<td>pl₂, pl₃, pl₄</td>
</tr>
<tr>
<td>s5</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁</td>
</tr>
<tr>
<td>s6</td>
<td>pl₁</td>
<td>pl₂, pl₃</td>
<td>pl₁, pl₂, pl₃</td>
<td>pl₁, pl₂, pl₃</td>
<td>pl₁</td>
<td>pl₁, pl₂, pl₃</td>
</tr>
<tr>
<td>s7</td>
<td>pl₁, pl₂</td>
<td>pl₁</td>
<td>pl₂</td>
<td>pl₂</td>
<td>pl₃</td>
<td>pl₂, pl₃</td>
</tr>
<tr>
<td>s8</td>
<td>pl₁</td>
<td>pl₃</td>
<td>pl₁</td>
<td>pl₁, pl₂, pl₃</td>
<td>pl₁</td>
<td>pl₁, pl₂</td>
</tr>
<tr>
<td>s9</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁, pl₂, pl₃</td>
<td>pl₁</td>
<td>pl₁, pl₂</td>
</tr>
<tr>
<td>s₁₀</td>
<td>pl₁</td>
<td>pl₃</td>
<td>pl₁, pl₂</td>
<td>pl₁, pl₂</td>
<td>pl₁</td>
<td>pl₁, pl₂</td>
</tr>
<tr>
<td>s₁₁</td>
<td>pl₁, pl₂, pl₃</td>
<td>pl₂</td>
<td>pl₂, pl₃</td>
<td>pl₂, pl₃, pl₄</td>
<td>pl₂</td>
<td>pl₂, pl₃, pl₄</td>
</tr>
<tr>
<td>s₁₂</td>
<td>pl₁, pl₂</td>
<td>pl₂</td>
<td>pl₂, pl₃, pl₄</td>
<td>pl₂, pl₃, pl₄</td>
<td>pl₁, pl₂, pl₃</td>
<td>pl₃, pl₄</td>
</tr>
<tr>
<td>s₁₃</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁</td>
<td>pl₁</td>
</tr>
<tr>
<td>s₁₄</td>
<td>pl₁, pl₂</td>
<td>pl₁, pl₂</td>
<td>pl₁, pl₂, pl₃</td>
<td>pl₂</td>
<td>pl₃, pl₄</td>
<td>pl₁, pl₂, pl₃</td>
</tr>
<tr>
<td>s₁₅</td>
<td>pl₂, pl₃, pl₄</td>
<td>pl₂, pl₃, pl₄</td>
<td>pl₂, pl₃, pl₄</td>
<td>pl₃, pl₄</td>
<td>pl₃, pl₄</td>
<td>pl₃, pl₄</td>
</tr>
<tr>
<td>s₁₆</td>
<td>pl₁, pl₂</td>
<td>pl₁, pl₂</td>
<td>pl₁, pl₂</td>
<td>pl₁, pl₂, pl₃</td>
<td>pl₁, pl₂</td>
<td>pl₂, pl₃, pl₄</td>
</tr>
</tbody>
</table>
Figure 15: Design space for each posture
8.2 Transmit power adaptation

Table 11 shows the results of the transmit power adaptation mechanism, where its performance is compared with the minimum energy needed according to the design space exploration (Table 9). The transmit power adaptation mechanism proposed in this thesis achieves the overall PRR requirement at the cost of 8.8% more energy than the optimal solution.

Table 11: Results per posture

<table>
<thead>
<tr>
<th>posture</th>
<th>average PRR (%)</th>
<th>average energy (µJ)</th>
<th>performance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>93</td>
<td>5.86</td>
<td>+9.7</td>
</tr>
<tr>
<td>P2</td>
<td>91</td>
<td>6.01</td>
<td>+10.1</td>
</tr>
<tr>
<td>P3</td>
<td>92</td>
<td>5.94</td>
<td>+9.4</td>
</tr>
<tr>
<td>P4</td>
<td>90</td>
<td>6.14</td>
<td>+7.5</td>
</tr>
<tr>
<td>P5</td>
<td>91</td>
<td>5.95</td>
<td>+9.0</td>
</tr>
<tr>
<td>P6</td>
<td>90</td>
<td>6.10</td>
<td>+7.0</td>
</tr>
<tr>
<td>average</td>
<td>91</td>
<td>6.00</td>
<td>+8.8</td>
</tr>
</tbody>
</table>

Figure 16 shows the PRR and the power level of node $s_5$ for posture P2. The power level is increased when the PRR decreases (sample 165-180) and decreased again when the PRR is above the required PRR (sample 180-200). Shown in Figure 17 the transmit power adaptation mechanism increases power when the PRR drops below the required minimum (sample 97-103 and 155-185). A complete set of graphs of all postures and nodes is given in Appendix A.

Table 12: Energy usage compared to fixed power levels

<table>
<thead>
<tr>
<th>posture</th>
<th>$p_1$ (%)</th>
<th>$p_1^4$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>+12.5</td>
<td>-15.6</td>
</tr>
<tr>
<td>P2</td>
<td>+15.4</td>
<td>-13.4</td>
</tr>
<tr>
<td>P3</td>
<td>+14.0</td>
<td>-14.4</td>
</tr>
<tr>
<td>P4</td>
<td>+17.9</td>
<td>-11.5</td>
</tr>
<tr>
<td>P5</td>
<td>+14.2</td>
<td>-14.3</td>
</tr>
<tr>
<td>P6</td>
<td>+17.1</td>
<td>-12.1</td>
</tr>
<tr>
<td>average</td>
<td>+15.2</td>
<td>-13.5</td>
</tr>
</tbody>
</table>

Running at a fixed power level will cost 5.21 µJ per frame for the lowest power
level ($pl_1$) and 6.94 $\mu$J per frame for the highest power level ($pl_4$). Running at power level $pl_1$ the average PRR over all postures is 50% and for $pl_4$ an average PRR of 97% is achieved. Table 12 compares the results of the transmit power adaptation mechanism with running at fixed power levels. The transmit power adaptation mechanism consumes 15.2% more energy than running at the lowest power level but does reach the PRR requirement. Compared to the highest power level, 13.5% less energy is consumed using the transmit power adaptation mechanism.

Nabi et al. [11] have presented a multi-hop protocol that improves PRR with 27% compared to a star-based architecture with a fixed power level. The energy consumption of their protocol is 2.5 times higher than a star-based protocol. The transmit power adaptation mechanism presented shows that at most 10% extra transmit energy is needed when using star-based architecture with variable power levels to achieve the same PRR requirement.
Figure 16: Results posture P5, node $s_2$
Figure 17: Results posture P5, node $s_6$
Figure 18: Results posture P5, node $s_{15}$
Table 13: Individual node PRR

<table>
<thead>
<tr>
<th>posture</th>
<th>$s_1$</th>
<th>$s_2$</th>
<th>$s_3$</th>
<th>$s_4$</th>
<th>$s_5$</th>
<th>$s_6$</th>
<th>$s_7$</th>
<th>$s_8$</th>
<th>$s_9$</th>
<th>$s_{10}$</th>
<th>$s_{11}$</th>
<th>$s_{12}$</th>
<th>$s_{13}$</th>
<th>$s_{14}$</th>
<th>$s_{15}$</th>
<th>$s_{16}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>93</td>
<td>94</td>
<td>71</td>
<td>93</td>
<td>100</td>
<td>100</td>
<td>93</td>
<td>99</td>
<td>98</td>
<td>89</td>
<td>92</td>
<td>100</td>
<td>92</td>
<td>84</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>92</td>
<td>92</td>
<td>93</td>
<td>93</td>
<td>100</td>
<td>85</td>
<td>95</td>
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<td>100</td>
<td>93</td>
<td>82</td>
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<td></td>
</tr>
<tr>
<td>P3</td>
<td>95</td>
<td>91</td>
<td>89</td>
<td>87</td>
<td>100</td>
<td>91</td>
<td>92</td>
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<td>91</td>
<td>83</td>
<td>100</td>
<td>92</td>
<td>83</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>93</td>
<td>88</td>
<td>88</td>
<td>88</td>
<td>98</td>
<td>91</td>
<td>88</td>
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<tr>
<td>P5</td>
<td>97</td>
<td>78</td>
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<td>100</td>
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<td>98</td>
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<tr>
<td>P6</td>
<td>92</td>
<td>85</td>
<td>90</td>
<td>88</td>
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<td>87</td>
<td>87</td>
<td>86</td>
<td>92</td>
<td>81</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>
8.3 Non-monotonic relation

Figure 18 shows that for node \(s_{15}\) and posture P5 the maximum power level still leads to a PRR below the required PRR. For this particular node, the average PRR is higher on power level \(p_{l3}\) than \(p_{l4}\). Figure 19 shows the PRR when the power level for node \(s_{15}\) is fixed to \(p_{l3}\) for posture P5. The transmit power adaptation mechanism proposed in this thesis cannot prevent this non-monotonic relation of power level and PRR. The result is that more energy is consumed than necessary and a lower PRR than possible is perceived.

It should be noted that the experiments for each power level were done independently. A possible explanation for this non-monotonic behavior is that the environmental conditions changed or the exact positions of the nodes on the body changed leading to different angles for the antennas.

![Graph showing PRR vs sample for different power levels](image)

Figure 19: Fixed power level \(p_{l3}\) posture P5, node \(s_{15}\)

Table 13 shows the individual results for all nodes and postures. Node \(s_{15}\) has a non-monotonic relation for all postures and does not meet the application requirement on PRR. The average PRR of all nodes (per posture) does meet the PRR requirement.

8.4 Link quality estimation

The transmit power adaptation mechanism relies on the PRR. Different link quality estimation (LQE) techniques may affect the performance of adaptation mechanisms such as transmit power adaptation. The performance of different link quality estimation (LQE) techniques for WBANs is experimentally studied in [13]. Due to the nature of WBANs, a LQE technique should react fast enough to follow the
changes in the link quality to avoid excessive packet loss. Their results show that the PRR is a stable metric which does not fluctuate too much when a single packet is lost.

Besides different LQE techniques, different parameters can be used to optimize each LQE technique. The window length $W$ can be changed for PRR (Equation 5). Increasing the window length will give a more stable control signal but will react less adequate to fluctuations of the PRR. The optimal value of $W$ also depends on the application and should be considered during design-time.
9 Conclusion

This thesis shows that a transmit power adaptation mechanism can be used to optimize energy consumption in WBANs. Efficient and reliable communication can be achieved with a combination of a transmit power adaptation mechanism and multi-hop routing.

9.1 Transmit power adaptation

A transmit power adaptation mechanism is presented that optimizes energy consumption for different postures. The proposed mechanism is not an optimal solution as it consumes on average 10% more power than needed to achieve a minimum application Packet Reception Ratio (PRR) requirement of 90%. The fact that no single configuration can be used that minimizes power for every posture indicates that some kind of power adaptation mechanism is needed in WBANs. Using a fixed (high) power level for each node will consume more energy than needed. The proposed transmit power adaptation mechanism optimizes the transmit energy of WBAN nodes with a PRR requirement in mind. The proposed implementation consumes more energy than necessary when a higher transmit power leads to lower PRR. An improvement would be to implement some kind of mechanism that can deal with this situation, keeping in mind the changing environment and posture changes that make prediction based on earlier samples unreliable.

9.2 Multi-hop strategies

The low quality and time-varying characteristics of wireless links in WBANs make reliable communication over these links hard to achieve. Robustness in a WBAN is in contradiction with minimizing transmit power. Solutions like multi-hop WBANs and gossiping strategies will make the end-to-end links in WBANs more robust and reliable but consume more energy due to receive power and retransmissions. Multi-hop mechanisms will increase the latency of data delivery. It should therefore be considered when even at highest transmit power a direct link to the gateway does not provide the required data delivery ratio. Combining transmit power adaptation and on-demand multi-hop strategies [11] can lead to an efficient mechanism.
10 Future work

This section describes possible improvements and future research areas for transmit power adaptation mechanisms in WBANs.

10.1 Dynamic posture changes

The proposed transmit power adaptation mechanism optimizes energy for fixed postures. Different postures are simulated but posture changes are not taken into consideration. In daily life posture transitions take place and a transmit power adaptation mechanism would be more robust and energy efficient if it could deal efficiently with such transitions. Not all posture transitions will be even likely in a real world situation. For example the posture change from 'sitting on a chair' to 'stand' will occur more often than the transition from 'sitting on a chair' to 'running'. An enhanced version of the proposed transmit power adaptation mechanism could take those posture changes into account to optimize energy consumption in a real world application.

10.2 Different radios

The proposed transmit power adaptation mechanism is tested with the MyriaNed hardware which has only four different power levels and a small range of transmit energy possibilities. A different radio with more than four distinct power levels gives a more finer scale and might perform better than the coarse MyriaNed nodes. More tests should be done with different hardware to validate the proposed transmit power adaptation mechanism. Examples of transceiver with more transmit power levels are Cypress CYRF7936 [2] or the Microchip MRF24XA [8].

10.3 Transmit power adaptation mechanism

The results of the guided search design space exploration show that the proposed mechanism in this thesis performs around 10% above the minimum energy that is needed to meet the PRR requirement for a particular posture. There is no common configuration of power levels that can satisfy the PRR requirement for all postures, but a more advanced controller might perform better. The CPU power that is needed for a more advanced control mechanism must not exceed the profit of a lower transmit power consumption.

The proposed transmit power adaptation mechanism aims at the lowest transmit energy needed for an application PRR requirement. This reduces the risk of interfering other WBANs in the neighbourhood. However, interference from other WBANs is not recognized and transmit power will be increased when the PRR is below the application requirement (due to interference). Further research might be done to recognize interference from other WBANs and lower transmit power in these situations.

10.4 Multi-hop WBANs

The approach presented by Nabi et al. [11] changes network topology from star to multi-hop when a link connection is insufficient. For the sensor nodes used in
this project, multi-hop techniques would not be energy efficient due to the high receive energy in comparison with the transmit energy. With the MyriaNed nodes one should only switch to multi-hop when the node is already operating at the highest power level in star configuration. Switching to multi-hop would improve robustness of the WBAN at the cost of higher energy consumption.
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References


Nordic Semiconductor. nRF24L01: Ultra low power 2.4GHz RF Transceiver, 2013.


A Results transmit power adaptation mechanism

The following sections show the PRR and power level for each node, ordered per posture. The postures considered in the experiments are given in Table 14 and were carried out with 15 sensor nodes and one gateway node. The node positions are shown in Figure 20.

Table 14: Postures considered in the experiments

<table>
<thead>
<tr>
<th>Reference</th>
<th>Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Sitting on a chair</td>
</tr>
<tr>
<td>P2</td>
<td>Sitting on the ground</td>
</tr>
<tr>
<td>P3</td>
<td>Standing</td>
</tr>
<tr>
<td>P4</td>
<td>Walking</td>
</tr>
<tr>
<td>P5</td>
<td>Lying down</td>
</tr>
<tr>
<td>P6</td>
<td>Running</td>
</tr>
</tbody>
</table>

Figure 20: Placement 15 nodes and gateway ($s_7$)
A.1 Posture P1

Figure 21: Results posture P1 (1)
Figure 22: Results posture P1 (2)
Figure 23: Results posture P1 (3)
Figure 24: Results posture P1 (4)
A.2 Posture P2

(a) Node $s_1$

(b) Node $s_2$

(c) Node $s_3$

(d) Node $s_4$

Figure 25: Results posture P2 (1)
Figure 26: Results posture P2 (2)
Figure 27: Results posture $P_2$ (3)
Figure 28: Results posture P2 (4)
A.3 Posture P3

Figure 29: Results posture P3 (1)
Figure 30: Results posture P3 (2)
Figure 31: Results posture P3 (3)
Figure 32: Results posture P3 (4)
A.4 Posture P4

Figure 33: Results posture P4 (1)
Figure 34: Results posture P4 (2)
Figure 35: Results posture P4 (3)
Figure 36: Results posture P4 (4)
A.5 Posture P5

Figure 37: Results posture P5 (1)
Figure 38: Results posture P5 (2)
Figure 39: Results posture P5 (3)
Figure 40: Results posture P5 (4)
A.6 Posture P6

Figure 41: Results posture P6 (1)
Figure 42: Results posture P6 (2)
Figure 43: Results posture P6 (3)
Figure 44: Results posture P6 (4)

(c) Node $s_{16}$