RESEARCH ARTICLE

Impact of priority differentiation on the bridged WBAN/WLAN healthcare networks

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ABSTRACT

In this work, we develop a prioritized bridging mechanism between the IEEE 802.15.6-based wireless body area networks (WBANs) and the IEEE 802.11e enhanced distributed channel access (EDCA)-based wireless local area network (WLAN) to convey the medical data to the medical center. We map the eight WBAN user priorities (UPs) into the four WLAN access categories (ACs) to provide the required quality of service and prioritization for the health variables generated by the WBAN nodes. By assignment of WBAN UPs with default medium access control parameters to eight different medical data streams and under the presence of ordinary nodes, we investigate the impact of WLAN AC differentiation by arbitrary inter-frame space (AIFS) and contention window (CW) on performance of medical and regular nodes’ data streams. The results of this work indicate that the AC differentiation by AIFS outperforms the differentiation by CW in the sense that it does not deteriorate the end-to-end delay of relayed WBAN traffic and ordinary WLAN traffic. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
wireless body area networks (WBANs); wireless local area networks (WLANs); wireless healthcare networks; medium access control mechanism; performance evaluation

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1. INTRODUCTION

To predict and diagnose the diseases and monitor the body’s response to treatments, a novel wireless technology-driven human body monitoring system was introduced, as wireless body area network (WBAN). The collected medical data in the WBAN must be transferred to a medical center, out of the WBAN, to be further processed and stored.

In this work, we bridge WBANs and wireless local area networks (WLANs) to build the wireless healthcare network. We adopt the IEEE 802.15.6 standard for the patient’s body network (WBAN) [1] because it has been specifically designed for wireless healthcare networks. Because IEEE 802.15.6 has strict quality of service (QoS) and priorities to transfer the medical data to the server, a QoS-enabled WLAN for the next hop is needed to preserve the end-to-end QoS. We adopt the IEEE 802.11e standard because the IEEE 802.11e enhanced distributed channel access (EDCA) provides QoS that can match requirements of IEEE 802.15.6 QoS [1]. EDCA introduces the contention-based medium access control (MAC) of the IEEE 802.11e standard. The bridge device is the hub of a WBAN and a station in the WLAN. The bridge communicates with the sensors and actuators inside the WBAN and conveys the medical data to the server through the WLAN.

In Figure 1, networking structure of a healthcare system including the WBANs, bridges, and the WLAN is depicted. Bridging WBANs and WLANs imposes lots of challenges that must be addressed for designing efficient and seamless communications in a healthcare network (Section 2). Setting the MAC parameters of the IEEE 802.15.6 and IEEE 802.11e EDCA standards affects the network performance. The priority differentiation in IEEE 802.11e EDCA is achieved by four differentiation parameters: amount of time a station senses the channel to be idle before backoff or transmission (arbitrary inter-frame space—AIFS), the length of contention window (CW) for backoff (the minimum and maximum CWs—CW_{min} and CW_{max}), and the duration a station may transmit after it successfully accesses the channel (transmission opportunity—TXOP). The priorities in the IEEE 802.15.6
standard are differentiated based on the minimum and maximum CWs \((C_{\text{Wmin}}\) and \(C_{\text{Wmax}}\). The WBAN differentiation parameters, \(C_{\text{Wmin}}\) and \(C_{\text{Wmax}}\), have been chosen according to IEEE 802.15.6. However, all four differentiation parameters of IEEE 802.11e EDCA \((C_{\text{Wmin}}, C_{\text{Wmax}}, \text{AIFS}, \) and \(\text{TXOP}\) are configurable.

In this work, we investigate the impact of access category (access category) differentiation through AIFS and CW in the WLAN on the performance of the (bridged) two-tier WBAN/WLAN healthcare network. We consider a network in which all eight default WBAN user priorities (UPs) are assigned to different data sensing streams belonging to most important health variables. The ordinary nodes transmit non-real time data generated by medical staff. The WLAN includes ordinary nodes in addition to the WBAN/WLAN bridges. Because OPNET \([2]\) does not have any module with implementation of the IEEE 802.15.6 standard, we have developed a detailed simulation model for IEEE 802.15.6. We have also developed the simulation model for the bridged IEEE 802.15.6-based WBAN/IEEE 802.11e EDCA-based WLAN healthcare network. By developing the simulation model, which precisely follow the IEEE 802.15.6 and IEEE 802.11e standards, we investigate the impact of priority differentiation of WLANs and WBANs on the healthcare network performance.

In our previous studies, we developed analytical models to investigate the performance of the IEEE 802.15.6-base in \([3,4]\) and IEEE 802.11e EDCA-based WLANs in \([5]\). The simulation models for the IEEE 802.15.6-based WBANs and the IEEE 802.11e EDCA-WLANs were separately validated. A single analytical model for the performance investigation of the two-tier bridged WBAN/WLAN healthcare network causes a large complexity because of two reasons. First, the individual analytical models for the IEEE 802.15.6 and IEEE 802.11e EDCA standard are complex. Second, the frame arrival process to the bridges follows a general distribution due to the output process characteristics of the contention-based MAC mechanism. This would lead to a \(G/G/1/K\) queuing model in the bridges, which significantly complicates the analytical modeling \([6]\). Because the large complexity of the analytical model shadows the research goals of this study and makes the paper difficult to follow and understand, we only present the simulation results in this paper.

Performance of IEEE 802.15.6 has been investigated through simulation and analytical models so far only in \([3,7,8]\). There are other works in the literature that address specific MAC protocols for WBANs (such as \([9,10]\)) or develop frameworks for the healthcare systems (such as \([11,12]\)). However, these studies do not evaluate the IEEE 802.15.6-based WBAN performance. Models for EDCA are more mature as presented in \([5,13–16]\). There are currently a few projects to support multiple wireless technologies in a single device such as \([17]\). However, no device has been developed for bridging between WBANs and WLANs. The authors in \([18]\) studied performance of a healthcare system that bridges IEEE 802.15.4-based WBANs and IEEE 802.11-based WLAN, but the authors did not address UPs neither in the WBANs nor the WLAN. To our best knowledge, there is no work in the literature that addresses bridging between the IEEE 802.15.6 and the IEEE 802.11e standards. In addition, this is the first work that investigates the impacts of bridged WBAN/WLAN priority differentiation on the overall healthcare network performance.

The remainder of this paper is organized as follows: Section 2 addresses the bridging mechanism between WBANs and WLAN. In Section 3, we investigate the performance of IEEE 802.15.6-based WBAN/IEEE 802.11e EDCA-based WLAN bridges and the regular WLAN nodes when the AC differentiation is performed through either AIFS or CW. Finally, Section 4 concludes the paper summarizing the findings of the study.


2. BRIDGING WBANs AND WLANs

2.1. IEEE 802.15.6-based WBAN

We deploy the IEEE 802.15.6 standard for communication in WBAN. According to the IEEE 802.15.6 standard there are eight different user priorities (UPs) in a WBAN that are differentiated by the minimum and maximum CW sizes ($CW_{\text{min}}$ and $CW_{\text{max}}$). The time is divided into beacon periods (superframes) by the hub. As depicted in Figure 2, a superframe is divided into exclusive access phases (EAP1 and EAP2), random access phases (RAP1 and RAP2), contention access phases (CAP), and type I/II access phases. Type I/II access phases are deployed for contention-free medium access mechanisms, whereas the other access phases are used for contention-based MAC schemes. The EAP periods can be only accessed for transmitting the $UP_k$ frames, whereas all UPs are allowed to access the medium during RAPs or a CAP.

In the IEEE 802.15.6 carrier sense multiple access (CSMA) mechanism, at the beginning of every backoff phase, a random number is chosen in the range of $[1, CW_{k,i}]$. The CW for a $UP_k$ node during the $i$th backoff phase is obtained as follows:

$$ W_{k,i} = \begin{cases} W_{k,\text{min}} = CW_{k,\text{min}}, & \text{if } i = 0 \\ \min (2W_{k,i-1}, CW_{k,\text{max}}), & \text{if } 2 \leq i \leq R \\ W_{k,i-1}, & \text{if } 1 \leq i \leq R \text{ and } i \text{ is even} \\ 2W_{k,i-1}, & \text{if } 1 \leq i \leq R \text{ and } i \text{ is odd} \end{cases} \quad (1) $$

where $CW_{k,\text{min}} = W_{k,0}$ and $CW_{k,\text{max}} = W_{k,m_k}$ indicate the minimum and maximum CW sizes for a $UP_k$ node.

The node locks its backoff counter when either the medium becomes busy for a transmission of the current time access phase is not accessible since the remaining time in the access phase is not sufficient for completing a data frame transaction. The node unlocks its backoff counter when the access phase is accessible for the node, the medium remains idle for the node’s AIFS period, and there is enough time for completing a data frame transaction. Upon unlocking the backoff counter, the node decrements its backoff counter by one for each idle CSMA slot that follows. We assume that the WBAN nodes transmit one data frame upon successful access to the medium. Another possibility, according to the standard, is that the nodes can transmit as many data frames as they have in their queues, during the access phase in which the medium is successfully accessed.

2.2. IEEE 802.11e EDCA-based WLAN

IEEE 802.11e EDCA function allows traffic differentiation for the stations in the network. EDCA delivers traffic on the basis of differentiating eight UPs mapped into four ACs. The differentiation is achieved by varying the following four differentiation parameters: amount of time a station senses the channel to be idle before backoff or transmission (AIFS), the length of CW for backoff ($CW_{\text{min}}$ and $CW_{\text{max}}$), and the duration a station may transmit after it acquires the channel (TXOP). Each AC has its own queue and channel access differentiation parameters.

With the IEEE 802.11e EDCA at the beginning of every backoff phase, a random number is chosen over the interval $[0, CW_k]$, where $CW_k$ is an integer within the range of two differentiation parameters of $CW_{k,\text{min}} = W_{k,0} - 1$ and $CW_{k,\text{max}} = W_{k,\text{max}} - 1$. The size of CW for a station of $AC_k$ for the $i$th backoff stage, $i = 0, \ldots, R$, has the value of

$$ CW_{k,i} = \begin{cases} 2W_{k,0}, & \text{if } 0 \leq i \leq m_k \\ 2^iW_{k,0} = W_{k,\text{max}}, & \text{if } m_k < i \leq R \end{cases} \quad (2) $$

where $CW_{k,\text{min}} = W_{k,0} - 1$ and $CW_{k,\text{max}} = W_{k,\text{max}} - 1$. Every station maintains a retry count taking an initial value of zero. The retry count is incremented after an unsuccessful medium access.

If the medium becomes busy during the backoff countdown, the counter remained locked until the medium is sensed idle again for the node’s AIFS period. Then, for every idle CSMA slot, the counter is counted down by one. Transmission commences when the backoff timer reaches zero. The fourth differentiation parameter of IEEE 802.11e EDCA standard is TXOP, as the length of the period in which the node has an uninterrupted access to the medium. TXOP is defined by a starting time and a maximum length (in seconds) and enables multi-frame transmission after single backoff process. TXOP = 0 means the node is able to transmit only a single data frame upon successful medium access.

![Figure 2. Layout of access phases in a WBAN superframe.](image-url)
2.3. WBAN–WLAN bridging

Bridging WBANs and WLANs imposes many challenges, which should be addressed for efficient and seamless communications in the healthcare networks. Using one or two interfaces in the WBAN/WLAN bridges is a challenging issue. Because the interfaces are inexpensive these days, we assume that the bridges (hubs) are equipped with two network interfaces. Selecting the frequency bands in which the WBAN nodes and the WLAN stations operate is another important challenge in the bridging design.

To improve the WBAN performance, we assume that the WBAN nodes operate on the frequency range of 2360–2400 MHz. Thus, they avoid the contention in the 2.4-GHz ISM band (which decreases their interference with the other wireless networks) and achieve the highest possible transmission rate, 971.4 kbps.

Another challenge relates to the operating channels of the neighboring WBANs in a wireless healthcare network. We assume that the WBANs in an area operate in different frequency channels to avoid mutual interference. Because the IEEE 802.15.6 standard provides numerous channels for WBANs in different frequency ranges and there are often a small number of WBANs in the short transmission range of a WBAN, this assumption is realistic. Table I indicates the number of WBAN channels in different frequency ranges. There are altogether 117 channels in the frequency bands of 2360–2400 MHz and 2400–2483.5 MHz. There can be different methods for choosing the operating channel. The MAC differentiation parameters set for WBAN and WLAN hops are shown in Table II. TXOP value is equal for all ACs in the WLAN although, through the experiments, we vary its value to study its impact on the network performance.

Mapping the WBAN UPs into WLAN ACs is another important challenge for bridging the WBANs and the WLAN. In case of the aggregated WBAN data frames, the number of aggregated frames, the UP of the data frames, and the size of the aggregated WLAN data frames must be considered. Making decision on all these issues depends not only on the network traffic loads but also on the network performance.

In this work, we assume that every four data frames with specific UPs are aggregated into a single WLAN data frame. A WBAN/WLAN bridge collects four \( UP_k, k = 0, \ldots, 7 \), WBAN data frames and aggregates them into a single WLAN data frame to be transferred to the medical server. In this work, we investigate the healthcare network performance under low to medium traffic. The WBAN data frame aggregation improves the system performance under medium to high traffic loads by decreasing the medium contention. Small packet sizes of some sensor nodes also justify the data frame aggregation in the WBAN/WLAN bridges. We map the WBAN UPs into WLAN ACs on the basis of the priorities of the WBAN data frames and traffic rates of all UPs, as shown in Table II.

We do not use request to send/clear to send (RTS/CTS) mechanism for accessing the medium in WBANs because according to our study in [19], deploying RTS/CTS mechanism is mostly counter-productive. However, we deploy

### Table I. Frequency band-dependent parameters.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol rate (ksps)</td>
<td>1875</td>
<td>1875</td>
<td>250</td>
<td>300</td>
<td>250</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Number of channels</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>48</td>
<td>12</td>
<td>38</td>
<td>79</td>
</tr>
<tr>
<td>Channel bandwidth (MHz)</td>
<td>0.30</td>
<td>0.50</td>
<td>0.40</td>
<td>0.50</td>
<td>0.40</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Table II. Wireless body area network (WBAN) user priority mapping into wireless local area network (WLAN) access categories (\( CW_m;CW \text{ min} \) and \( CW_M;CW \text{ max} \)).

<table>
<thead>
<tr>
<th>WBAN</th>
<th>WLAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic designation</td>
<td>Traffic designation</td>
</tr>
<tr>
<td>CWm;CW \text{ min}</td>
<td>AIFS;CWm;CW \text{ min}</td>
</tr>
<tr>
<td>AC</td>
<td>AIFS;CWm;CW \text{ max}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UP</th>
<th>Traffic designation</th>
<th>CWm;CW \text{ min}</th>
<th>CW_M;CW \text{ max}</th>
<th>AIFS</th>
<th>CWm;CW \text{ min}</th>
<th>CW_M;CW \text{ max}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Background</td>
<td>16 64</td>
<td>0 Background</td>
<td>7 31</td>
<td>1023</td>
<td>2 63</td>
<td>1023</td>
</tr>
<tr>
<td>1 Best effort</td>
<td>16 32</td>
<td>1 Best effort</td>
<td>5 31</td>
<td>1023</td>
<td>2 31</td>
<td>511</td>
</tr>
<tr>
<td>2 Excellent effort</td>
<td>8 32</td>
<td>2 Video</td>
<td>3 31</td>
<td>1023</td>
<td>2 15</td>
<td>255</td>
</tr>
<tr>
<td>3 Controlled load</td>
<td>8 16</td>
<td>3 Voice</td>
<td>2 31</td>
<td>1023</td>
<td>2 7</td>
<td>127</td>
</tr>
<tr>
<td>4 Video</td>
<td>4 16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Voice</td>
<td>4 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Media data or</td>
<td>2 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>network control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Emergency</td>
<td>1 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AIFS, arbitrary inter-frame space; CW, contention window; UP, user priority; AC, access category.
3. PERFORMANCE EVALUATION OF WIRELESS HEALTHCARE NETWORK

In this section, we investigate the wireless communication performance of a healthcare network that is composed of WBANs and a WLAN. Deploying appropriate types and numbers of different medical sensors in the WBANs is a challenging topic in the wireless healthcare systems study. We choose a challenging set of health variables that include electrocardiography, electroencephalography, blood pressure, glucose, oxygen saturation, temperature, respiration rate, and physical activity. The application scenario is chosen to aim a wireless healthcare system that collects the body’s vital health information. The WBANs consist of 20 healthcare sensors. The way the sensors are divided into eight UPs, their traffic rates, and their frames payload sizes are shown in Table III. Selecting an appropriate UP for medical data is also a challenging issue. The priority setting depends on the patient’s medical monitoring requirements and also types and numbers of different sensor nodes. In this work, the UP values for the sensor data are set on the basis of traffic intensity, importance, and time-tolerance of the medical data.

The purpose of this paper is to explore settings of IEEE 802.11 MAC parameters, which will give a better performance of the bridged WBAN/WLAN network. The medical data frames arrive to the WBAN nodes according to the Poisson distribution with the mean arrival rates shown in Table III. Although the medical traffic of the sensor nodes could be periodic or Poisson, we choose Poisson process because we want to obtain conservative performance bounds. Although the inter-arrival times of the data frames to the WBAN nodes are exponentially distributed, their arrivals to the bridges do not follow the Poisson distribution. Instead, the bridges’ data frame arrival process is a function of output process of the IEEE 802.15.6 MAC.

We set the EAP1 length to 0.1 s whereas RAP1 length is set to 0.5 s, unless explicitly specified. The values of EAP1 and RAP1 are set according to our study in [20]. The control frames and headers are transmitted at 91.9 kbps while we assume that the payload is transmitted at 971.4 kbps. The transmission rates are set to achieve better network performance. Smaller transmission rates are also possible according to the standard. We set the retransmission limit to seven for all UPs.

The payloads of WLAN data frames are transmitted with the transmission rate of 5.5 Mbps, whereas the headers are transmitted with the transmission rate of 1 Mbps. The retransmission limit in the WLAN is set to seven for all ACs. We evaluate the network performance for the cases where all WLAN ACs operate with TXOP = 0 or TXOP = 5000 μs.

In the WLAN, there are two types of nodes: WBAN/WLAN bridges (WBAN hubs) and regular WLAN nodes. The WBAN/WLAN bridges are simply called bridges hereafter. The hub in a WBAN (bridge) collects the data frames from all the healthcare nodes in its body area network. We deploy four performance descriptors for investigating the performance of the network:

- Mean data frame response time (WBAN/WLAN).
- Successful medium access probability (WLAN).
- Mean number of successfully transmitted frames during a TXOP access (WLAN).
- Successful transmission probability during a TXOP access (WLAN).

The performance descriptors are computed for two sets of nodes in the network: the bridges and the regular WLAN nodes.

<table>
<thead>
<tr>
<th>Table III. Healthcare nodes are spread into eight user priorities (UPs).</th>
</tr>
</thead>
<tbody>
<tr>
<td>UP</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

ECG, electrocardiography; EEG, electroencephalography; EMG, electromyography; AC, access category.
We assume that the WBAN nodes operate over a Rician-faded channel between the nodes and the hub, in which the bit error rate (BER) is a function of channel quality, diversity order, and signal-to-noise ratio values for all UPs. It is more accepted that Rice distribution is the best suited scheme for modeling the WBAN channel fading [21–23]. In addition, we assume that the WBAN nodes deploy the quadrature phase shift keying (QPSK) modulation scheme to achieve the highest data frame transmission rate. The resulting data frame error rates due to the fading channel affect the mean data frame response time in the WBAN.

We calculate the BER of QPSK in Rician fading channels for different UPs according to [4]. Based on the positions and types of healthcare nodes we set the Rician factors for different UPs as \((K_0, K_1, K_2, K_3, K_4, K_5, K_6, K_7) = (1.5, 4, 3, 2.5, 1.5, 1.5, 4)\). The diversity order, \(L\), is set to 1 for all UPs. We obtain the average BERs for all UPs as shown in Table IV.

OPNET simulator [2] is used for simulation modeling of the healthcare network, including the WBANs and the WLAN. The simulation model follows assumptions and definitions from the IEEE 802.15.6 and IEEE 802.11e standards.

Figure 3 shows the data frame mean response time in the WBAN. The plot depicts the time as the duration between the moment when the sensor generates the data frame until the moment when the data frame is successfully transmitted to the hub. The results indicate that increasing the RAP length, while the EAP length is constant, slightly improves the response time for all UPs. Because the data frame sizes and the data frame error rates are different for different UPs, the priority is not the only factor affecting the data frame access delay.

As a result of considering results from Figure 3, throughout this work, we set the default length of RAP1 to 0.5 s and the length of EAP1 to 0.1 s, unless explicitly indicated.

We evaluate cases where the WLAN contains 10 bridges and 3 or 10 regular WLAN nodes. All regular nodes generate data frames of all ACs with the payload size of 100 B.

Table IV. Simulation parameters.

<table>
<thead>
<tr>
<th>WLAN slot size</th>
<th>20 μs</th>
<th>WBAN slot size</th>
<th>125 μs</th>
</tr>
</thead>
<tbody>
<tr>
<td>WLAN SIFS</td>
<td>10 μs</td>
<td>WBAN SIFS</td>
<td>62.5 μs</td>
</tr>
<tr>
<td>WLAN AIFS_2</td>
<td>312.5 μs</td>
<td>WBAN EAP_1</td>
<td>0.1 s</td>
</tr>
<tr>
<td>WLAN AIFS_1</td>
<td>437.5 μs</td>
<td>WBAN RAP_1</td>
<td>0.5 s</td>
</tr>
<tr>
<td>WLAN AIFS_2</td>
<td>687.5 μs</td>
<td>WBAN EAP_2 = RAP_2 = CAP</td>
<td>0 s</td>
</tr>
<tr>
<td>WLAN AIFS_3</td>
<td>937.5 μs</td>
<td>WBAN type I/II</td>
<td>0 s</td>
</tr>
<tr>
<td>WLAN PLCP header</td>
<td>40 b</td>
<td>WBAN PLCP header</td>
<td>41 b</td>
</tr>
<tr>
<td>WLAN PLCP preamble</td>
<td>12 symbols</td>
<td>WBAN PLCP preamble</td>
<td>90 b</td>
</tr>
<tr>
<td>WLAN RTS packets size</td>
<td>160 b</td>
<td>WLAN CTS packets size</td>
<td>112 b</td>
</tr>
<tr>
<td>WLAN ACK</td>
<td>112 b</td>
<td>WBAN ACK</td>
<td>72 b</td>
</tr>
<tr>
<td>WLAN frequency band</td>
<td>2.4 GHz</td>
<td>WBAN frequency band</td>
<td>2360–2400 MHz</td>
</tr>
<tr>
<td>WLAN payload transmission rate</td>
<td>5.5 Mbps</td>
<td>WBAN payload transmission rate</td>
<td>971.4 kbps</td>
</tr>
<tr>
<td>WLAN control frame/header transmission rate</td>
<td>1 Mbps</td>
<td>WBAN control frame/header transmission rate</td>
<td>91.9 kbps</td>
</tr>
</tbody>
</table>

WLAN, wireless local area network; WBAN, wireless body area network; SIFS, short inter-frame space; AIFS, arbitrary inter-frame space; RTS, request to send; CTS, clear to send; EAP, exclusive access phase; RAP, random access phase; ACK, acknowledgement.

Figure 3. Mean data frame response time in a wireless body area network when RAP1 length varies (length of EAP1 = 0.1 s).
Table V. Bit error rate (BER) values for user priorities in wireless body area network.

<table>
<thead>
<tr>
<th>BER₀</th>
<th>BER₁</th>
<th>BER₂</th>
<th>BER₃</th>
<th>BER₄</th>
<th>BER₅</th>
<th>BER₆</th>
<th>BER₇</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.95866*10⁻⁶</td>
<td>2.31524*10⁻⁶</td>
<td>5.0085*10⁻⁶</td>
<td>5.0085*10⁻⁶</td>
<td>7.21*10⁻⁵</td>
<td>13.95866*10⁻⁵</td>
<td>13.95866*10⁻⁵</td>
<td>2.31524*10⁻⁵</td>
</tr>
</tbody>
</table>

WLAN nodes (3 and 10), the TXOP value (0 and 5000 µs), and the type of AC differentiation (AIFS differentiation and CW differentiation) vary. The mean response time of the bridges’ frames indicates the time duration between the moment when the frame, composed of four WBAN data frames, is created until the moment when the data frame is successfully transmitted to the WLAN access point. The plots in Figure 4 show that when there are three regular WLAN nodes in the network, differentiation by CW or AIFS does not considerably affect the response time of the bridges’ data frames. However, when there are 10 regular WLAN nodes in the network (larger number of contending nodes), yet under low to moderate traffic loads, the differentiation through AIFS outperforms the differentiation through CW. Small CW sizes increase the collision probability for the contending nodes and trigger transition to early saturation for the wireless networks based on CSMA with collision avoidance. The plots indicate that the non-zero TXOP values can slightly help to avoid the early saturation when AC differentiation is performed through CW sizes. When TXOP = 0 (a single data frame can be transmitted upon a successful medium access) and there are 10 regular WLAN nodes, the lowest AC data frames response times exceed 0.04 s when the regular WLAN nodes generate approximately 10 and 8 frames per second (fps), for the cases where the differentiation is performed through AIFS and CW, respectively. In case of TXOP = 5000 µs and 10 regular WLAN nodes, when AC differentiation is carried out through AIFS and CW the mean response times of data frames exceed 0.25 s at approximately 14 and 12 fps, respectively.

Figure 5 shows the mean response time of data frames generated by regular WLAN nodes in the WLAN when there are 10 WBAN/WLAN bridges and
- there are 3 or 10 regular WLAN nodes;
- TXOP = 0 or TXOP = 5000 µsec;
- AC differentiation is done through AIFS or CW.
The data frame mean response time indicates the duration between the moment when the frame is created until the moment when it is successfully transmitted. The results confirm that the IEEE 802.11e EDCA mechanism is very sensitive to the network traffic load because of the small CW sizes, which causes larger data frame access delay when there is a larger number of contending nodes in the network. AC differentiation through AIFS improves the data frame response time for the bridges and regular WBAN nodes since it provides moderate differentiation. The results also indicate that it is necessary to set TXOP values to non-zero values.

Figures 6 and 7 show the successful medium access probability of bridges and regular nodes in the WLAN, respectively, where the number of regular WLAN nodes, TXOP values, and differentiation method vary. The plots indicate that applying priority differentiation in an EDCA-based WLAN using CW sizes would cause excessive frame collisions in the second hop and would result in large end-to-end frame access delays. The results show that if the CW is used for AC differentiation, the higher priority ACs experience larger collision probability while they access the medium more often because of small CW sizes. The successful medium access probability also depends on the data frame sizes. The AC1 has the largest aggregated WBAN data frames on average (900 B for AC0, 1100 B for AC1, 400 B for AC2, and 600 B for AC3). Larger data frames cause higher number of retransmissions due to the error-prone channel. The results also show that larger number of regular WLAN nodes and smaller TXOP values considerably decrease the successful medium access probability of bridges to transmit their data frames to the access point.

Figure 6(a), (c), (e), and (g) shows the successful medium access probability for the bridges when AIFS is deployed for AC differentiation. In this case, higher priority aids an AC to have larger successful medium access probability, except for AC1 and AC2 under low load. The reason is the larger number of AC2 nodes compared with that of AC1 nodes, which causes higher collision probability. Figure 7(a), (c), (e), and (g) represent the successful medium access probability for regular WLAN nodes which have identical numbers of nodes, data frame sizes, and data frame arrival rates. In this case, it is clear that higher priority ACs enjoy higher successful transmission rate. Thus, applying AIFS differentiation parameter for prioritization aids higher priority ACs to more efficiently use the medium. On the contrary, Figures 6(b), (d), (f), and (h) and 7(b), (d), (f), and (g) indicate that if CW is used for AC differentiation, the higher ACs experience smaller successful medium access probability because of smaller CWs. However, because larger numbers of bridges belong to AC0 and AC2, compared with AC1 and AC3, respectively, according to Figure 6(b), (d), (f), and (g), AC0 and AC2 have smaller medium access probability compared with AC1 and AC2, respectively.

Figure 8 represents the mean number of successfully transmitted data frames during a TXOP access for bridges in the WLAN. Figure 8(a)–(d) shows the successful
(a) 3 regular nodes, TXOP=0, AIFS differentiation
(b) 3 regular nodes, TXOP=0, CW differentiation
(c) 10 regular nodes, TXOP=0, AIFS differentiation
(d) 10 regular nodes, TXOP=0, CW differentiation
(e) 3 regular nodes, TXOP=5000 μsec, AIFS differentiation
(f) 3 regular nodes, TXOP=5000 μsec, CW differentiation
(g) 10 regular nodes, TXOP=5000 μsec, AIFS differentiation
(h) 10 regular nodes, TXOP=5000 μsec, CW differentiation

Figure 6. Successful medium access probability in the wireless local area network (WLAN). The parameters are set to 10 bridges, 3 or 10 regular WLAN nodes with all four access categories, BER = 2 × 10⁻⁶, and TXOP=0 or TXOP=5000 μs.

(a) 3 regular nodes, TXOP=0, AIFS differentiation
(b) 3 regular nodes, TXOP=0, CW differentiation
(c) 10 regular nodes, TXOP=0, AIFS differentiation
(d) 10 regular nodes, TXOP=0, CW differentiation
(e) 3 regular nodes, TXOP=5000 μsec, AIFS differentiation
(f) 3 regular nodes, TXOP=5000 μsec, CW differentiation
(g) 10 regular nodes, TXOP=5000 μsec, AIFS differentiation
(h) 10 regular nodes, TXOP=5000 μsec, CW differentiation

Figure 7. Successful medium access probability in the wireless local area network (WLAN). The parameters are set to 10 bridges, 3 or 10 regular WLAN nodes with all four access categories, BER = 2 × 10⁻⁶, and TXOP=0 or TXOP=5000 μs.
Priority differentiation on the bridged WBAN/WLAN healthcare networks

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Figure 8. Mean number of successfully transmitted frames during a transmission opportunity (TXOP) access for hubs in the wireless local area network (WLAN). The parameters are set to 10 bridges, 3 or 10 regular WLAN nodes with all four access categories, BER $= 2 \times 10^{-5}$, and TXOP $= 0$ or TXOP $= 5000 \mu s$.

Figure 9. Mean number of successfully transmitted frames during a transmission opportunity (TXOP) access for regular nodes in the wireless local area network (WLAN). The parameters are set to 10 bridges, 3 or 10 regular WLAN nodes with all four ACs, BER $= 2 \times 10^{-5}$, and TXOP $= 0$ or TXOP $= 5000 \mu s$. 
transmission rate during the TXOP access since TXOP=0. The frame would be corrupted only because of the error-prone channel because there is no contention when the TXOP period is successfully obtained. AC\textsubscript{2} (encapsulating WBAN UP\textsubscript{4} and UP\textsubscript{5} data frames) and AC\textsubscript{1} (including WBAN UP\textsubscript{2} and UP\textsubscript{3} data frames) have the highest and lowest successful transmission rates because their data frames on average are the smallest (400 B) and largest (1100 B), respectively. In addition, when TXOP = 0 the number of regular nodes does not affect the mean number of successfully transmitted frames during the TXOP period. However, when TXOP = 5000 \mu s larger number of regular WLAN nodes causes larger number of data frame transmissions within TXOP periods for bridges. According to Figure 8(e) and (f), when there are smaller number of regular WLAN nodes in the network, under low to moderate traffic loads, AC differentiation by CW causes smaller number of transmissions during the TXOP periods compared with the case when AIFS is used for differentiation. However, when there is a larger number of regular WLAN nodes (10 nodes), the AC differentiation by CW causes larger number of data frame transmissions during the TXOP periods as a result of higher contention on the medium.

Figure 9 shows the mean number of successfully transmitted data frames for regular WLAN nodes. When TXOP = 0, the mean number of successfully transmitted data frames represents the successful data frame transmission rate during the TXOP period where there is no contention. Figure 9(a)–(d) indicates that the successful data frame transmission rate for all ACs does not depend on number of nodes or the AC differentiation approach. The probabilities are identical for all ACs because they all have equal BERs. Figure 9(e)–(h) confirms that for smaller number of regular WLAN nodes, under low to moderate traffic loads, the differentiation through CW causes smaller number of data frame transmissions during the TXOP period because the nodes access the medium more often, compared with the case where AIFS is deployed for AC differentiation. In case of 10 regular WLAN nodes when AIFS is used for AC differentiation and all regular WLAN nodes generate 14 fps for each AC, AC\textsubscript{0}, AC\textsubscript{1}, AC\textsubscript{2}, and AC\textsubscript{3} successfully transmit on average 2.6, 1.8, 1.4, and 1.3 frames in the TXOP period, respectively. However, for the same condition when CW is deployed for AC differentiation, AC\textsubscript{0}, AC\textsubscript{1}, AC\textsubscript{2}, and AC\textsubscript{3} successfully transmit on average 5.2, 3.5, 2.2, and 1.5 frames in the TXOP period, respectively. The reason is higher collision probability for all ACs when CW is deployed for AC differentiation.

4. CONCLUSION

In this paper, we presented a simulation study of the performance of bridging the IEEE 802.15.6-based WBANs and the IEEE 802.11e EDCA-based WLAN for a wireless healthcare network. We have developed a detailed and accurate simulation model of the two-tier WBAN/WLAN bridged healthcare network. We mapped the eight WBAN UPs into the four WLAN ACs to preserve the end-to-end QoS in the wireless healthcare networks. The generated WBAN traffic belongs to the all eight UPs, and the WBAN data streams are aggregated and transferred to the medical center through a WLAN that also contains ordinary nodes. We evaluated the healthcare network performance on the basis of two AC differentiation mechanisms in the WLAN: differentiation by CW sizes and by AIFS. Although AC differentiation can be carried out by CW\textsubscript{min} and CW\textsubscript{max}, the results of this work indicate that it leads to an aggressive differentiation resulting in lower overall network performance. Small CW sizes increase the collision probability for the contending nodes and trigger transition to early saturation in the WLAN. This would cause higher contention in the second hop and results in large end-to-end frame delays. In addition, the saturation in the WLAN causes buffer overflow in the bridges (WBAN hubs) resulting in the medical data loss which is undesirable. Therefore, in order to have moderate differentiation and lower frame collision probability, this work confirms that AIFS is more appropriate for differentiating the WLAN ACs.

REFERENCES

applications, In Proc. the 4th International Conference on Ubiquitous Information Management and Communication, Suwon, Korea, Jan 2010.


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Research Article

Impact of priority differentiation on the bridged WBAN/WLAN healthcare networks

Saeed Rashwand and Jelena Misic

In this work, we develop a prioritized bridging mechanism between the IEEE 802.15.6-based wireless body area networks (WBANs) and the IEEE 802.11e enhanced distributed channel access-based wireless local area network (WLAN) to convey the medical data to the medical center. The results of this work indicate that the access category differentiation by arbitrary inter-frame space outperforms the differentiation by contention window in the sense that it does not deteriorate the end-to-end delay of relayed WBAN traffic and ordinary WLAN traffic.
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Q3: Industrial, Scientific, and Medical (ISM)

Q5: Table V: a sentence should be added to page 5 line 63: "The simulation parameters are set according to Table IV."

Q7: page 2. line 27: AIFS is equal to AIFSN*slot duration + SIFS.

Q8: Electrocardiogram (ECG)

Q9: Electroencephalogram (EEG)

Q10: Electromyogram (EMG)

Q12: page 6 line 18 Table IV should be changed to Table V.

Q14: Physical Layer Convergence Procedure (PLCP)

Q17: IEEE WCNC: IEEE Wireless Communications and Networking Conference

Other references have full title.

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