Bridging Between IEEE 802.15.6 and IEEE 802.11e for Wireless Healthcare Networks

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Abstract

While many of the technologies envisaged for use in wireless healthcare systems are available today little is known about their interplay. The collected medical data in a Wireless Body Area Network (WBAN) must be transferred to a medical center for further processing and storage. Therefore, second wireless hop is needed before access to the wired network is achieved. The main focus of this research is to investigate the performance of interconnection between patient's IEEE 802.15.6-based WBAN and the stationary (e.g., hospital room or ward) IEEE 802.11e-based Wireless Local Area Network (WLAN). We introduce a Quality of Service (QoS)-based bridging mechanism between the WBANs and the WLAN to interconnect human body monitoring networks and the WLAN access point. We use strong prioritizing parameters among 8 traffic priorities in WBAN as recommended by the standard. However, we deploy Arbitrary Inter-Frame Space (AIFS) for differentiating the WLAN Access Categories (ACs) to provide relatively mild differentiation and decrease the frame collision probability. By employing simulation models we investigate the impacts of network and prioritizing Medium Access Control (MAC) parameters on the bridges' performance. The results of the paper indicate the large impact of the numbers of WBANs and regular WLAN nodes and their traffic rates on the healthcare network performance. In addition, the performance is significantly improved by setting appropriate MAC parameters for the network and deploying aggregation mechanisms.

Keywords: Wireless Body Area Networks (WBANs), Wireless Local Area Networks (WLANs), Wireless Healthcare Networks, Medium Access Control Mechanism, Performance Evaluation

I. Introduction

Increasing the number of ageing population and the people who need continuous health monitoring and rising the costs of health care have triggered the concept of the novel wireless technology-driven human body monitoring, so called Wireless Body Area Network (WBAN). A WBAN is a body monitoring network which aims to predict and diagnose any diseases and monitor the response of the body to treatments. The WBAN is composed of small and intelligent wireless medical sensors which are worn or implanted into the tissues. The collected medical data are transmitted to a medical center through a hub to be further processed and stored.

The body monitoring sensor network increases the chance to diagnose cardiac arrhythmias earlier in "at risk" groups and provides continuous checking of the disease progression and patient's response to

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any treatment initiated. The concept of ubiquitous and pervasive human well-being monitoring sensor system with regard to physical, physiological, and biomedical parameters in any environment for all people provides invaluable benefits. The system is becoming a reality with the important advances in sensor, low power CPU technology, wireless data transmission technologies, increased battery duration, reduced energy consumption, and power scavenging.

The main focus of this research is to investigate the performance of interconnection of patient's WBAN and the (e.g., hospital room or ward) WLAN. WBANs must support the combination of reliability, Quality of Service (QoS), low power, high data rate and non-interference to address the breadth of WBAN applications. Due to the lack of a wireless communication standard which supports the specific requirements of WBANs, the IEEE 802.15.6 standard was developed, optimized for low power devices and operation on, in or around the human body [1]. We adopt the IEEE 802.15.6 standard for the patient's body network. For WLAN hop, we adopt IEEE 802.11e standard since it provides the relative QoS for the stations in the network [2].

In this work, we introduce a bridging mechanism between WBANs and WLAN which provides end-to-end QoS. We investigate the impacts of a variety of network parameters on performance of interconnection between IEEE 802.15.6 and IEEE 802.11e. We deploy a simulation model for investigating the performance of the interconnected WBAN-WLAN network. Although we have developed analytical models for single hop IEEE 802.15.6-based and IEEE 802.11e Enhanced Distributed Channel Access (EDCA)-based networks [3], [4], [5], in this work we use simulations in order to avoid large computation complexity of analytical models. In this paper, we study how the number of patients in the healthcare network, the number of other devices in the WLAN, channel quality, WBAN and WLAN prioritizing MAC parameters affect the performance of the patient's healthcare network.

The remainder of this paper is organized as follows: Section II discusses the related work. Section III addresses the bridging mechanism between WBANs and WLAN. In Section IV we investigate the network performance by varying a variety of network parameters. Finally, Section V concludes the paper summarizing the findings of the study.

II. Related Work

In the recent years, a large body of work related to WBANs has appeared in the literature. In [6] the authors provide a comprehensive survey on WBANs. There are currently several research groups throughout the world which focus on design and implementation of a WBAN. The researchers have employed different wireless technologies in their projects in the field of wireless short-range connectivity, such as the IEEE 802 familly of WPANs, WLANs, Bluetooth and Zigbee. Most of the currently existing projects of WBANs employ IEEE 802.15.4 standard as the wireless communication technology [7], [8].

There are currently a few works in the literature which investigate the performance of an IEEE 802.15.6-based network. In [9] the authors developed a simple model to evaluate the theoretical throughput and delay limits of IEEE 802.15.6-based collision-free networks assuming an ideal channel. The developed model does not consider the User Priorities (UPs) and access phases. In [10] we studied the performance of the IEEE 802.15.6 MAC under saturation condition. A node in saturation condition always has a data frame in its buffer. Saturation regime analysis is computationally less complex and leads to conservative performance bounds. A WBAN must operate under non-saturation regime in order to prevent large buffer overflows. In [11], the authors investigated the IEEE 802.15.6-based WBAN performance in terms of packet loss rate, delay, and throughput, by developing a simulation model. In [3] we investigated the performance of IEEE 802.15.6-based WBANs under non-saturation regime through analytical and simulation models. In [4] we developed analytical and simulation models to study the performance of an IEEE 802.15.6-based WBAN operating over a Rician-faded channel.

Much more is known about prioritizing mechanisms within IEEE 802.11e EDCA. There is a large of body of work in the literature which studies the performance of IEEE 802.11e standard. Examples of analytical and simulation studies of EDCA single hop prioritization include [12], [13], [14], [15], [16], [17], [5], [18].

The authors in [19] studied performance of a healthcare system which bridges IEEE 802.15.4-based WBANs and IEEE 802.11-based WLAN, but the authors did not address user priorities neither in the WBANs nor the WLAN. To the best of our knowledge there is no work in the literature which evaluates bridging the IEEE 802.15.6 and IEEE 802.11e standards to compose a wireless healthcare network.

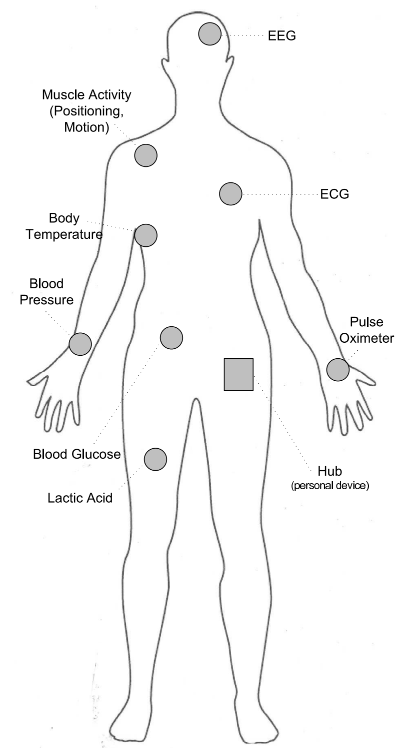


Fig. 1. The locations of medical sensors in the considered WBAN

III. QoS-based Bridging of WBAN and WLAN

In this section, we first describe the structure of the WBAN/WLAN two-tier healthcare network, which we consider in this work. A major component of the healthcare network is the WBAN. Each patient has a WBAN on his/her body, including medical sensors and a hub. The WBAN operates as the network coordinator and collects all the medical data from the sensors. A medical WBAN is depicted in Fig. 1. The collected medical data by the hub is partly processed, including data aggregation, compression and encryption. The processed data needs to be transmitted to a destination out of the WBAN. The destination could be a medical server to store and maintain all the medical records. The data is further processed by the server to extract the vital health information. In order to provide an unobtrusive healthcare network for the patient, the WBAN hub must communicate with the external source by a wireless connection. WLAN is an appropriate option for transferring the data between the WBAN hub and the medical information center. Reliability, high transmission rate, and cost-effectiveness are a few features of the WLANs which make them appropriate to be used as a building block of the healthcare network. The processed medical data by the hub is transferred to the server through the WLAN access point. Patients may have a different set of medical sensors based on their medical needs. In this work, we assume that all patients have an identical set of medical sensors in their WBANs. We have selected the sensors for comprehensive human body health monitoring [20].

As an instance for the healthcare network we consider a hospital in which patients and medical staff reside. In addition to the WBANs which represent the patients in the hospital the medical staff may carry other wireless devices such as laptops, cellphones, and Personal Digital Assistants (PDAs). The medical staff may also connect to the internet through the same WLAN access point. The patients and the medical staff could be at different floors of the hospital which is covered by a single WLAN access point. In this work, we model a healthcare network which includes both WBANs as the patients' body networks and the regular WLAN nodes as the medical staff's wireless devices. The layout of the healthcare network, which could span a hospital floor is shown in Fig. 2, or run over multi-floors hospital is shown in Fig. 3. The WBAN/WLAN bridges, simply called bridges hereafter, communicate with the central medical server (wireless access point as the first destination) while the regular WLAN nodes may communicate with another server or any other nodes.

WBAN/WLAN bridge devices could be implemented by adding a WLAN network adaptor to the WBAN hubs. The bridge would be the hub of the WBAN and a station in the WLAN. The bridge communicates with the sensors and actuators inside the WBAN and conveys the medical data in the WLAN to the healthcare medical center.

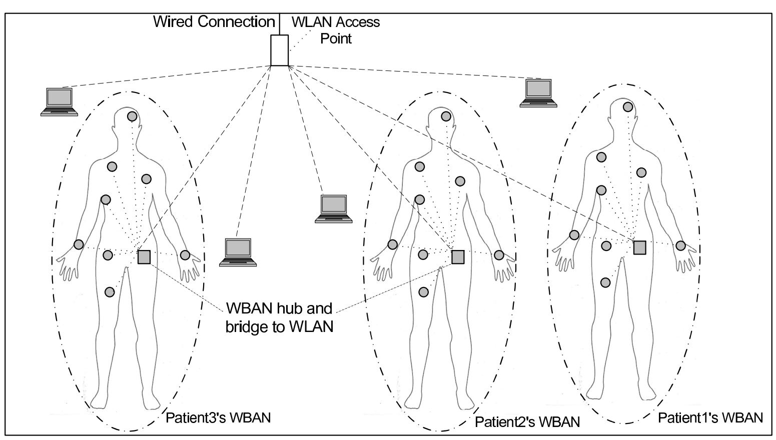


Fig. 2. Networking structure of two hop healthcare wireless network

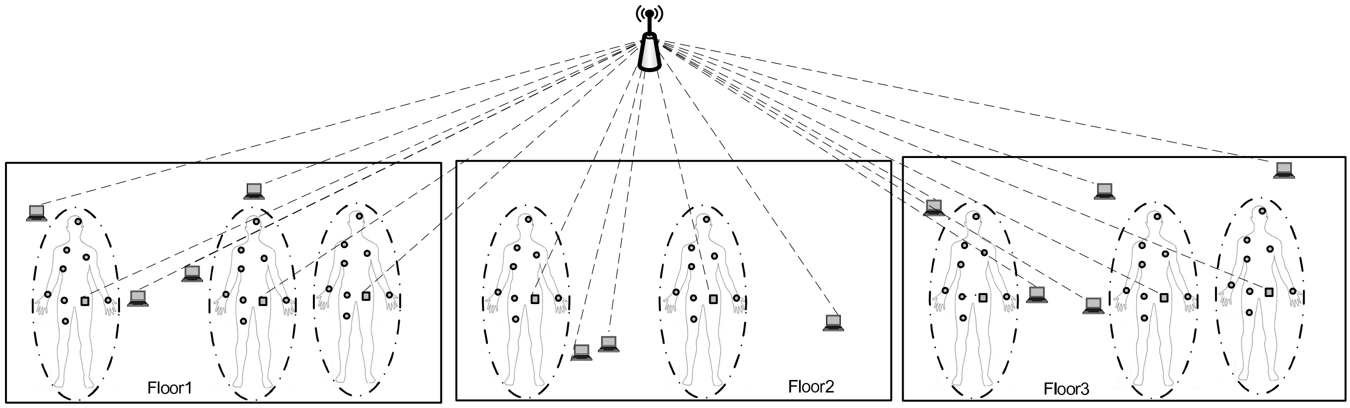


Fig. 3. Networking structure of two hop multi-floors healthcare network

Since IEEE 802.15.6 has strict 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. The IEEE 802.11e EDCA provides QoS which can match requirements of IEEE 802.15.6 QoS. IEEE 802.11e EDCA function is able to provide traffic differentiation among traffic classes similar to the IEEE 802.15.6.

This section consists of three subsections; First, we briefly introduce the contention-based mechanism of the IEEE 802.15.6 standard. Second, we briefly describe the IEEE 802.11e EDCA mechanism for accessing the medium. Finally, we discuss the challenges for bridging the IEEE 802.15.6 and the IEEE 802.11e standards and we develop our solution to bridge the WBANs and WLAN for the healthcare network.

A. IEEE 802.15.6-based WBAN

We deploy the IEEE 802.15.6 standard for communication in WBAN. According to the standard there are 8 different User Priorities (UPs) in a WBAN which are differentiated by minimum and maximum Contention Window sizes (CW_{min} and CW_{max}). The time is divided into beacon periods (*superframes*) by the hub (the network coordinator). The contention-based access methods for obtaining the allocations in IEEE 802.15.6 are either Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) if narrowband PHY (Physical Layer) is chosen or Slotted Aloha in case of using Ultra-Wideband (UWB) PHY. In this work, we consider the narrowband PHY. In addition, we assume the WBAN nodes operate in beacon mode with superframe boundaries; At the beginning of every superframe a beacon is transmitted on the medium to provide time referenced allocations. As depicted in Fig. 4 a superframe is divided into Exclusive Access Phases (EAP1 and EAP2), Random Access Phases (RAP1 and RAP2), and Contention Access Phases (CAP), and Type I/II Access Phases. Type I/II APs are indicated for contention-free medium access mechanisms while the other APs are used for contention-based MAC schemes. The EAP periods can be only accessed for transmitting the UP_7 frames while all UPs are allowed to access the medium during RAPs or a CAP.

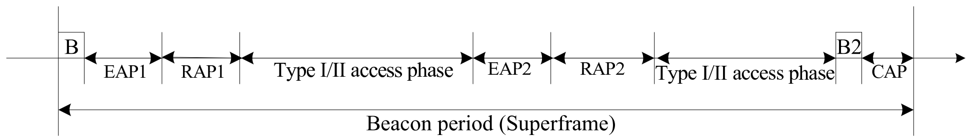


Fig. 4. Layout of access phases in a beacon period (superframe) for beacon mode

According to the IEEE 802.15.6 CSMA mechanism, at the beginning of every backoff phase a random integer number is chosen using the uniform distribution in the range $[1, CW_{k,i}]$, as the backoff count for a node of UP_k, where $CW_{k,i} = W_{k,i}$ for $i = 0..R$. The data frame is dropped if the number of retransmissions during a backoff process exceeds the maximum retry limit R. The contention window for a node of UP_k during the i-th backoff phase is obtained as follows:

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

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

The node locks its backoff counter when any of the following events occurs:

- The backoff counter is reset upon decrementing to 0.
- The channel is busy due to a transmission on the medium. If the channel is busy because the node detected a frame transmission, the channel remains busy until at least the end of the frame transmission without the node having to re-sense the channel.
- The current time is outside the access phases where the node can transmit. Any RAP or CAP if UP does not have the highest value, or is outside any EAP, RAP, or CAP if UP has the highest value.

- The current time is at the start of a CSMA slot within an EAP, RAP, or CAP, but the time between the ends of the slot and the EAP, RAP, or CAP is not long enough to complete a frame transaction.

The node unlocks its backoff counter when both of the following conditions are met:

- The channel has been idle for Short Inter-Frame Space (SIFS) within an access phase in which the node can access the medium.
- The time duration between the current time plus a CSMA slot and the end of the EAP, RAP, or CAP is long enough to complete a frame transaction.

Upon unlocking the backoff counter, the node decreases its backoff counter by one for each idle CSMA slot that follows. Upon having the backoff counter of 0 the node has obtained a contended allocation. We assume that the WBAN nodes transmit one data frame during an access to medium.

B. IEEE 802.11e EDCA-based WLAN

IEEE 802.11e EDCA function allows traffic differentiation for the stations in the network. EDCA delivers traffic based on differentiating 8 UPs mapped into 4 Access Categories (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 (Arbitrary Inter-Frame Space - AIFS), the length of contention window for backoff (CW_{min} and CW_{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. The EDCA provides a better quality of service to higher priority ACs, in which AC_3 and AC_0 are the highest and the lowest priority ACs, respectively. However, due to the probabilistic nature of channel access, it cannot provide hard QoS guarantees such as strict delay bound. The differentiation parameters of the EDCA are described below:

- A station which needs to initiate a data frame transmission performs a backoff procedure. The backoff count value for an AC_k station is an integer drawn from a uniform distribution over the interval $[0, CW_k]$, where CW_k is an integer within the range of two differentiation parameters of $\mathrm{CW}_{k,min} = W_{k,0} - 1$ and $CW_{k,max} = W_{k,max} - 1 = W_{k,m_k} - 1$. The station starts the backoff procedure with CW set to $CW_{k,min}$. Whenever there is an unsuccessful access to the medium CW

is changed to $2(CW + 1) - 1$ until reaching the maximum value, $CW_{k,max}$. The size of contention window for a station of AC$_k$ for the i-th backoff stage, $i = 0, ..., R$, has the value of

$$W_{k,i} = \begin{cases} 2^i W_{k,0}, & \text{if } 0 \leq i \leq m_k \\ 2^{m_k} W_{k,0} = W_{k,max}, & \text{if } m_k < i \leq R \end{cases} \tag{2}$$

Every station maintains a retry count taking an initial value of zero. The retry count is incremented after an unsuccessful medium access.

- A station which needs to transfer a data frame listens to the medium to determine whether there is any activity during each backoff slot. If no medium activity is detected for the duration of a particular backoff slot, the backoff counter is decremented by one. Otherwise, the backoff countdown is suspended. If the medium is busy the AC$_k$ station defers until the medium is sensed idle for a period of time equal to AIFS$_k$ = AIFSN$_k * \omega$ + SIFS, where ω is the CSMA slot size. After AIFS$_k$, the station continues decreasing the backoff counter if the counter was paused due a transmission on the medium. Otherwise, the station generates a random backoff period for an additional deferral time before the transmission if it is the beginning of a backoff phase. 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 time 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.

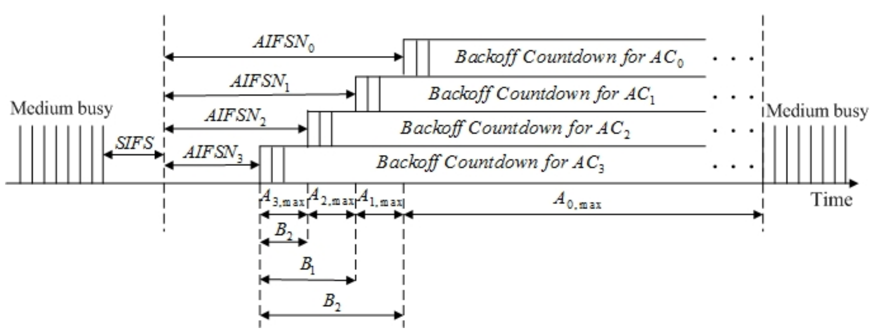


Fig. 5. Prioritizing EDCA stations using AIFS$_k$ differentiation parameter

TABLE I
FREQUENCY BAND DEPENDENT PARAMETERS IN IEEE 802.15.6

Frequency Band (MHz)	402 - 405	420 - 450	863 - 870	902 - 928	950 - 956	2360 - 2400	2400 - 2483.5
Symbol Rate (ksps)	187.5	187.5	250	300	250	600	600
number of channels	10	12	14	48	12	38	79
Channel Bandwidth (MHz)	0.30	0.50	0.40	0.50	0.40	1.00	1.00
Header Transmission Rate (kbps)	57.5	57.5	76.6	91.9	76.6	91.9	91.9
Maximum Payload Transmission Rate (kbps)	455.4	187.5	607.1	728.6	607.1	971.4	971.4

C. *WBAN-WLAN bridging challenges*

Bridging the WBAN and the WLAN imposes lots of challenges which must be considered for designing efficient and seamless communications in the healthcare network. In the following, we discuss the issues which are important in the design of bridges in wireless healthcare systems.

- Deploying one or two network interfaces in the WBAN-WLAN bridges is a challenging issue in the design of the wireless healthcare networks. If the bridge has a single network interface, the interface has to operate in both WBAN and WLAN. Though having only one interface decreases the bridge's cost, it imposes a lot of design and implementation challenges. In order to be able to operate in both networks (working based on different standards) serious re-configurations of PHY and MAC parameters are required. In addition, due to the different characteristics of the WBAN and WLAN environments and the standards the operating antennas for the networks should also be different. To be able to operate in both networks, the interface has to perform the time sharing between the WBAN and the WLAN which degrades the bridge performance in both networks. By deploying two network interfaces, the bridge is able to support simultaneous communications in the networks. Bridges with two network interfaces have the potential to support higher data rates compared with single interface ones. Since the interfaces are inexpensive these days, we assume that the bridges (hubs) are equipped with two network interfaces.
- An important challenge is related to the frequency bands in which the WBAN nodes and the WLAN stations operate. The WLAN stations operate in 2.4GHz ISM band with 11 channels in North America for high data rate transmission of 5.5 Mbps and 11 Mbps. The WBAN nodes can operate in more extensive frequency ranges as shown in Table I. Choosing an appropriate frequency band for WBANs affects the healthcare network performance. Operating on the license-free 2.4GHz frequency band

TABLE II
WBAN USER PRIORITY MAPPING INTO WLAN ACCESS CATEGORIES

<table>
<tr><th colspan="4">WBAN</th><th colspan="5">WLAN</th></tr>
<tr><th>UP</th><th>Traffic designation</th><th>CWmin</th><th>CWmax</th><th>AC</th><th>Traffic designation</th><th>AIFSN</th><th>CWmin</th><th>CWmax</th></tr>
<tr><td>0</td><td>Background (BK)</td><td>16</td><td>64</td><td rowspan="2">0</td><td rowspan="2">Background (BK)</td><td rowspan="2">7</td><td rowspan="2">31</td><td rowspan="2">1023</td></tr>
<tr><td>1</td><td>Best effort (BE)</td><td>16</td><td>32</td></tr>
<tr><td>2</td><td>Excellent effort (EE)</td><td>8</td><td>32</td><td rowspan="2">1</td><td rowspan="2">Best effort (BE)</td><td rowspan="2">5</td><td rowspan="2">31</td><td rowspan="2">1023</td></tr>
<tr><td>3</td><td>Controlled load (CL)</td><td>8</td><td>16</td></tr>
<tr><td>4</td><td>Video (VI)</td><td>4</td><td>16</td><td rowspan="2">2</td><td rowspan="2">Video (VI)</td><td rowspan="2">3</td><td rowspan="2">31</td><td rowspan="2">1023</td></tr>
<tr><td>5</td><td>Voice (VO)</td><td>4</td><td>8</td></tr>
<tr><td>6</td><td>Media data or network control</td><td>2</td><td>8</td><td rowspan="2">3</td><td rowspan="2">Voice (VO)</td><td rowspan="2">2</td><td rowspan="2">31</td><td rowspan="2">1023</td></tr>
<tr><td>7</td><td>Emergency or medical event report</td><td>1</td><td>4</td></tr>
</table>

leads to low network performance for WBANs since the band is overcrowded by many network technologies like IEEE 802.15.1 and IEEE 802.15.4. To improve the WBAN performance and decrease its interference with the other wireless networks, it is reasonable that the WBAN nodes operate on non-ISM frequency bands. In this work, we assume that the WBAN nodes operate on the frequency range of 2360 - 2400 MHz to avoid the contention on the 2.4GHz ISM band and achieve the highest possible data frame transmission rate, 971 kbps. Moreover, the lower the channel frequency is, the higher PHY raw transmission rate can be achieved. Therefore, the WBAN nodes and the WLAN stations do not interfere during their transmissions since they operate on different frequency bands.

- Another concern in the design of the wireless healthcare networks is that if the neighbouring WBANs in an area should perform Frequency-Division Multiple Access (FDMA) or Time-Division Multiple Access (TDMA). Since performing TDMA requires tight synchronization among all the nodes of the WBANs and due to the availability of a plenty of channels for WBANs, it is reasonable to perform FDMA for the WBANs. In this work, we assume that the WBANs in an area operate in different frequency channels to avoid mutual interference.
- Setting the MAC parameters of the IEEE 802.15.6 and IEEE 802.11e EDCA standards also affects the network performance. The WBAN differentiation parameters, CW_{min} and CW_{max}, are constant according to IEEE 802.15.6. However, all four differentiation parameters of IEEE 802.11e EDCA (CW_{min}, CW_{max}, AIFS, and TXOP) are configurable. Though AC differentiation can be done by CW_{min} and CW_{max} we don't differentiate the ACs in the WLAN by the contention window sizes since it leads to an aggressive differentiation. Small contention window sizes increase the collision

probability for the contending nodes and trigger transition to early saturation for the CSMA/CA-based wireless networks, as indicated in [10], [12]. The results of our study in [10] show that the IEEE 802.15.6 is very sensitive to the network traffic load because of the small contention window sizes. Applying priority differentiation in EDCA-based WLAN using contention window sizes would cause excessive frame collisions in the second hop and results in large end-to-end frame access delays. Therefore, in order to provide moderate differentiation of traffic classes in the second hop we differentiate the ACs in the IEEE 802.11e EDCA-based WLAN by AIFS values. AIFS values provide the opportunity for higher priority ACs to have higher successful transmission rates by allocating dedicated CSMA slots, as shown in Fig. 5. AIFS differentiation decreases the overall collision probability in the network by providing more transmission chances for higher priority ACs. Differentiation through AIFS outperforms the differentiation through the contention window sizes in terms of collision probability. 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, though through the experiments we vary it's 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. The data frames arriving to the bridges/hubs from the WBAN nodes belong to a specific UP. There is a large number of options to transfer the collected medical data to the WLAN access point. As an option, every received WBAN data frame can be individually transmitted to the WLAN access point. Another option is frame aggregation before transmission over the WLAN. Compressing the WBAN data frames by the hub undoubtedly improves the wireless healthcare network performance. However, data compression in the hubs needs higher processing and storage capabilities. Therefore, in this work we assume that the hubs do not perform any data compression. In case of aggregating the WBAN data frames into a single WLAN data frame, 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 not only depends on the network traffic rates but also on the network performance. In this work, we examine two cases; in the first one, every four data frames with specific UPs are aggregated into a single WLAN data frame. In the second one,

TABLE III
HEALTHCARE NODES ARE SPREAD INTO 8 UPS (NN: NUMBER OF NODES, TL: TRAFFIC LOAD PER PACKET, PS: PAYLOAD SIZE, AC: MAPPED INTO ACCESS CATEGORY)

UP	Node	NN	TL	PS	AC
7	ECG	1	2 p/s	150 B	3
	EEG	1	2 p/s	150 B	
6	EEG	2	2 p/s	150 B	3
5	EEG	1	2 p/s	150 B	2
	Blood Pressure	1	2 p/s	150 B	
4	Glucose	1	1 p/s	50 B	2
	Oxygen Saturation	1	1 p/s	50 B	
	Temperature	1	1 p/s	50 B	
	Respiration Rate	1	1 p/s	50 B	
3	Physical Activity	2	2 p/s	50 B	1
2	EMG	2	2 p/s	500 B	1
1	ECG	2	2 p/s	150 B	0
0	EEG	4	1 p/s	300 B	0

every WBAN data frame is converted to a single WLAN data frame for transmission in the WLAN. We map the WBAN UPs into WLAN ACs based on the priorities of the WBAN data frames and traffic rates of all UPs, as shown in Table II.

IV. PERFORMANCE EVALUATION OF WIRELESS HEALTHCARE NETWORK; INTERCONNECTED WBAN-WLAN

In this section, we investigate the performance of wireless communications in a healthcare network which is composed of WBANs interconnected to single WLAN. The WBANs consist of 20 healthcare sensors (8 EEG sensors, 3 ECG sensors, 2 Physical Activity sensors, 2 EMG sensors, 1 Blood Pressure sensor, 1 Glucose sensor, 1 Oxygen Saturation sensor, 1 Temperature sensor, and 1 Respiration Rate sensor). The medical sensors have been positioned on the body as shown in Fig. 1. The way the sensors are spread into 8 UPs, their traffic rates, and their frames payload sizes are shown in Table III. We have set the UPs for the medical data according to their delay-sensitivity and required bandwidth [20]. This is not a unique way for setting the parameters and assigning UPs to the medical data. Although the numbers and types of sensors on each patient can be different, for obtaining conservative performance results, we assume that each WBAN contains all sensors depicted in Table III. We set the retransmission limit to 7 for all UPs. In this work, we have considered single-hop WBAN and single-hop WLAN. In the overall network, the regular WLAN nodes and the WBAN/WLAN bridges have uniform spatial distribution.

Except for RAP1, the lengths of the other APs could be set to zero. The results of our study in [3] indicate that short EAP and RAP lengths generally degrade the network performance. We set the EAP1 length to 0.1 sec while RAP1 length is set to different values (varying between 0.5 sec and 1.2 sec), but identical for all WBANs. We consider the CSMA mechanism running in narrowband PHY. We assume that the hub operates in the beacon mode with superframe boundaries. All nodes are synchronized to support the contention-based mechanism of IEEE 802.15.6. We do not use RTS/CTS mechanism for accessing the medium in WBANs since according to our study in [21], [3] deploying RTS/CTS mechanism is mostly counter productive. The control frames and headers are transmitted at 91.4 kbps while we assume that the payload is transmitted at 971.6 kbps. We assume an error-prone channel having the constant Bit Error Rate (BER).

The payloads of WLAN data frames are transmitted with the transmission rate of 5.5 Mbps while the headers are transmitted with the transmission rate of 1 Mbps. The retransmission limit in the WLAN is set to 7 for all ACs. We deploy RTS/CTS mechanism for accessing to the medium in the WLAN. We evaluate the network performance for the cases where all WLAN ACs operate with TXOP=0 and TXOP= $5000 \mu sec$.

Based on how the bridge forwards the medical data to the access point we design two scenarios. In the first scenario, every four frames destined to a specific AC are aggregated (encapsulated) into a single WLAN data frame, without performing any data compression, and transmitted to the server. Data frames can have different sizes. In the second scenario, we investigate the network performance where the data frames received from the sensors are individually transmitted to the server.

We study the impacts of a variety of WBAN/WLAN parameters on the overall network performance. We deploy four performance descriptors for investigating the network performance, including WBAN/WLAN mean data frame response time, WBAN/WLAN successful medium access probability, mean number of successfully transmitted frames during a TXOP access, and successful transmission probability during a TXOP access. The performance descriptors are computed for two sets of nodes in the network; the bridges and the regular WLAN nodes.

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 Poission process since we want to obtain conservative performance bounds. Though the inter-arrival times of the data frames to the WBAN nodes are exponentially distributed, their arrivals to the hubs, which is a function of output process, do not follow the Poisson distribution. Data frame inter-arrival times for regular WLAN nodes are exponential distributed.

Since the signal transmission in WBANs takes place around or in the human body, the channel fading significantly affects the error performance of the the WBANs. We assume that the WBAN nodes operate over a Rician-faded channel between the nodes and the hub, in which the BER is a function of channel quality, diversity order, and Signal to Noise Ratio (SNR) values for all UPs. According to the research in [4], Rician distribution is the best option for WBAN channel modeling. As indicated in [4], the Rician factors have been chosen based on the positions and types of the medical sensors. We set the Rician factors in this work for different medical sensors based on the research findings in [4]. 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 as follows:

$$BER_{QPSK-Rice} = G(0, \frac{\pi}{2}, \overline{\gamma_b}, L, K_R, 1) \tag{3}$$

where $\overline{\gamma_b} = \frac{\overline{\gamma_c}}{2}$, $\overline{\gamma_c} = \frac{1}{2N_0}$ represents the average SNR per channel, N_0 is the power spectral density of the complex Gaussian random processes for the channels, and K_R is the Rician factor, and we have

$$G(\theta_1, \theta_2, \overline{\gamma}, L, K_R, d) = \frac{e^{-LK_R}}{\pi} \int_{\theta_1}^{\theta_2} \frac{exp(\frac{LK_R}{1+(\overline{\gamma}d^2/(K_R+1)sin^2\theta)})}{[1 + (\overline{\gamma}d^2/(K_R+1)sin^2\theta)]^L} \, d\theta \tag{4}$$

Based on the positions and types of healthcare nodes we set the Rician factors for different UPs as:

$$(K_0, K_1, K_2, K_3, K_4, K_5, K_6, K_7) = (1.5, 4, 3, 3, 2.5, 1.5, 1.5, 4) \tag{5}$$

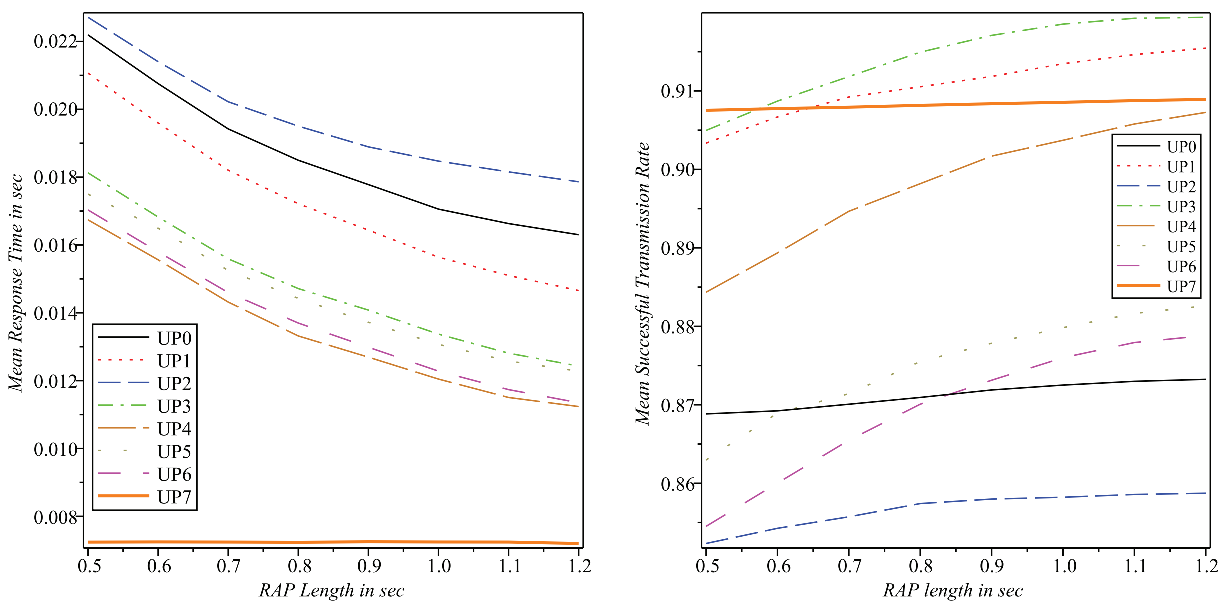
The diversity order, L, is set to 1 for all UPs. The value of $\overline{\gamma_c} = \frac{1}{2N_0}$ is set to 10 dB. By deploying the above formula and the parameters we obtain the average BERs for all UPs as shown in Table IV. In WLAN channel we assume constant BERs. A transmitted frame in the WLAN is assumed to be corrupted if at least one bit of the frame is corrupted. A frame is successfully transmitted if all the bits are correctly received.

TABLE IV
BER VALUES FOR UPs IN WBANs

BER_0	BER_1	BER_2	BER_3	BER_4	BER_5	BER_6	BER_7
0.0001395866	0.0000231524	0.000050085	0.000050085	0.0000721	0.0001395866	0.0001395866	0.0000231524

Opnet simulator [22] is used for simulation modeling of the 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.

In all plots in this section, the lines with the line-styles *thin solid* (black), *dot* (red), *dash* (blue), *dash-dot* (green), *long-dash* (gold), *space-dot* (khaki), *space-dash* (magenta), and *thick solid* (coral) represent user priorities, 0, 1, 2, 3, 4, 5, 6, and 7, respectively.



(a) Mean Data Frame Response Time in WBAN

(b) Mean Successful Transmission Rate in WBAN

Fig. 6. Mean data frame response time and average successful transmission rate in a WBAN when RAP1 length varies (length of EAP1 = 0.1 sec)

In Fig. 6 (a) the mean response time of data frames in the WBAN is depicted. The mean data frame response time in WBAN is defined as the time 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, improves the response time for all UPs. At the beginning of an RAP period the collision probability is larger since other nodes without

UP_7 unlock their backoff counter after the backoff count lock during EAP phases. In addition, longer EAP phases leads to more competition for the nodes since they have shorter accessible periods. Since 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 frames access delay. In addition, Fig. 6 (a) indicates that increasing the RAP lengths does not considerably decrease the delay. Fig. 6 (b) shows the successful transmission rates for all UPs. The rate indicates the percentage of times in which the node successfully transmit the data frame. The plot shows how increasing the RAP length improves the successful transmission rates. For the same reasons as mentioned in this paragraph, upon RAP/EAP ratio increase the successful transmission rates of the WBAN nodes are improved.

As a result of considering results from Fig. 6, throughout this work, we set the default length of RAP1 to 0.5 sec and the length of EAP1 to 0.1 sec, unless explicitly indicated. We have chosen the values for RAP and EAP phases because they provide reasonable delay and we are looking for conservative performance boundaries. In this work, for each set of parameters we have run the simulation for 1200 superframes.

A. Aggregating WBAN data frames to be transmitted to the server

In the first scenario, the bridge aggregates four WBAN data frames into a WLAN data frame. Since the aggregated data frames may include the data frames from different UPs, the data frames vary in size based on the including WBAN frames. We investigate the network performance under the impacts of different MAC and network parameters, including the number of regular WLAN nodes, the traffic rates of the regular nodes, data frame error rate, TXOP lengths and WBAN access phases lengths. Default number of bridges in the WLAN is set to 10 unless explicitly specified.

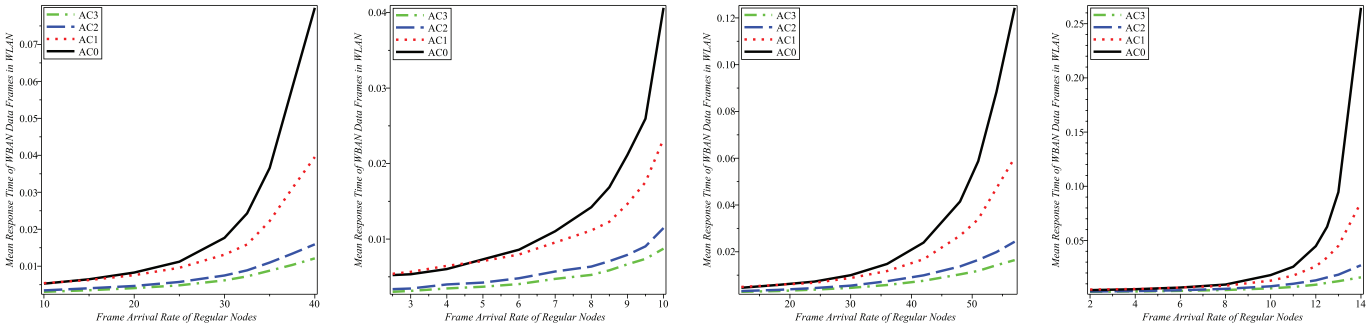
Impact of number of regular WLAN nodes on network performance

In the first experiment, we consider two cases; where the number of WLAN regular nodes is equal to 3 and 10, respectively. All regular nodes generate data frames of all ACs with the payload size of 100B.

Frame inter-arrival time of regular nodes are exponentially distributed with the mean values as indicated in the plots, unless explicitly specified. The BER for both cases are set to a constant value of $2 * 10^{-5}$.

The mean response time of the aggregated WBAN data frames in WLAN indicates the time duration between the moment since 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. In Fig. 7 we show the mean response time of the aggregated data frames in the WLAN for the cases where TXOP is equal to 0 and 5000 μsec. When TXOP = 0 the nodes are able to transmit a single data frame upon a successful medium access. When the nodes are able to transmit more than one data frame during TXOP period the performance is enhanced for all ACs. We only show the WLAN's results where the WLAN data frame response time is tolerable for both bridges and regular WLAN nodes. We avoid displaying the results when the network is unstable (i.e. saturated [5]). The network is unstable when an AC is in saturation regime. Let us assume that 0.04 sec is the tolerance threshold for the bridges' data frame response time in the WLAN. According to Fig. 7, in case of TXOP=0, the response time of AC_0 data frames exceeds the threshold when the regular nodes' data frame arrival rate rises above 35 fps and 10 fps, when there are 3 and 10 regular WLAN nodes in the network, respectively. In case of TXOP=5000 μsec, Fig. 7 (c) and (d) indicate that the response time tolerance threshold is exceeded when the regular WLAN nodes' arrival rate passes 46 fps and 11 fps where 3 and 10 WLAN regular nodes are active, respectively. The results show the the large impact of the number of regular nodes in the WLAN on the bridges' performance. The AC_1 has the largest aggregated WBAN data frames on average (900 B for AC_0, 1100 B for AC_1, 400 B for AC_2, and 600 B for AC_3). However, larger data frames cause higher number of retransmissions due to the error-prone channel. The remaining time in the TXOP period after finishing the data frames in the queue is return by the node for the use of other nodes in the network.

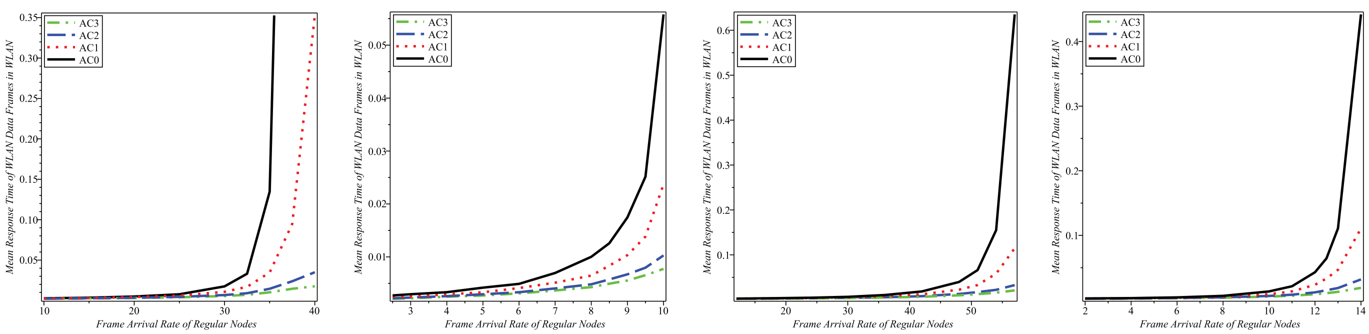
Fig. 8 shows the mean response time of data frames generated by regular WLAN nodes in the WLAN. The time indicates the duration between the moment when the frame is created until the moment when it is successfully transmitted. When TXOP=0, the frame arrival rate varies between 10 fps and 40 for 3 regular nodes, while the frame arrival rate varies between 2 fps and 10 fps for 10 regular WLAN nodes. The results indicate that larger TXOP value decreases the data frame response time for all ACs,



(a) 3 regular nodes, TXOP=0 (b) 10 regular nodes, TXOP=0 (c) 3 regular nodes, TXOP=5000 μsec (d) 10 regular nodes, TXOP=5000 μsec

Fig. 7. Mean response time of aggregated WBAN data frames in the WLAN with 3 and 10 regular WLAN nodes which have all four ACs. TXOP = 0 and TXOP =5000 μsec. BER = $2 * 10^{-5}$. There are 10 bridges in the WLAN.

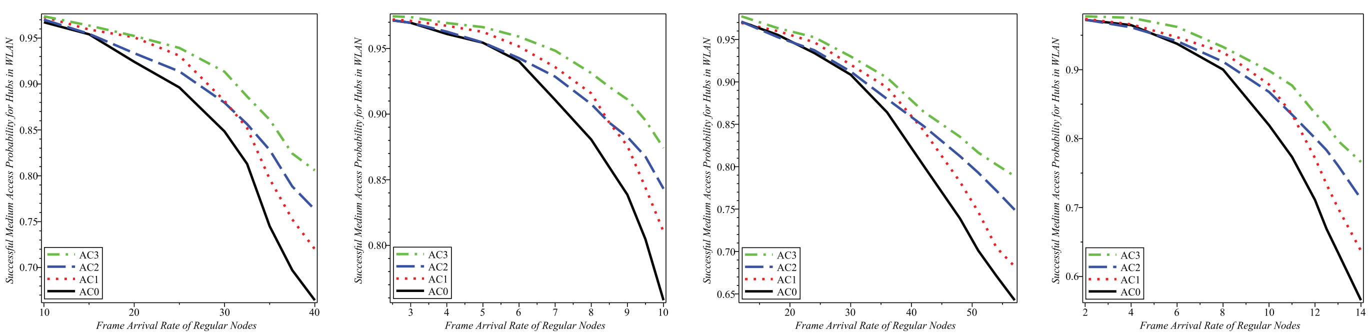
as expected. As indicated in Fig. 8, when there are 3 regular WLAN nodes, TXOP=0 causes network transition to saturation condition for AC_0 WLAN data frames at 35 fps while this condition occurs at 57 fps when TXOP=5000 μsec, which is approximately 63% improvement. The results indicate that setting non-zero value for TXOP is a must in the network which improves the network performance.



(a) 3 regular nodes, TXOP=0 (b) 10 regular nodes, TXOP=0 (c) 3 regular nodes, TXOP=5000μsec (d) 10 regular nodes, TXOP=5000μsec

Fig. 8. Mean response time of WLAN data frames in the WLAN with 3 and 10 regular WLAN nodes which have all four ACs. TXOP = 0 and TXOP =5000 μsec. BER = $2 * 10^{-5}$. There are 10 bridges in the WLAN.

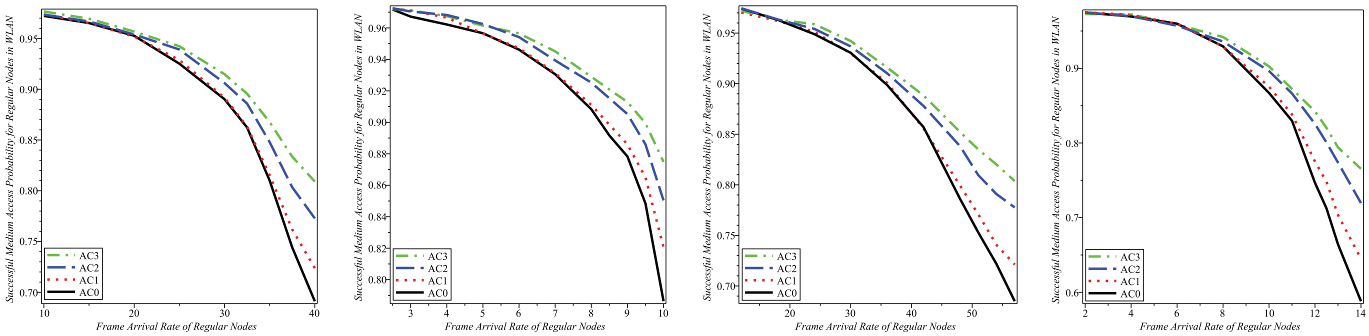
Fig. 9 and Fig. 10 show the successful medium access probability of bridges and regular WLAN nodes in the WLAN, respectively. The results show that increasing the number of regular nodes in the WLAN considerably decreases the successful medium access probability of bridges to transmit their data frames to the access point. The higher priority ACs in bridges do not always achieve higher successful medium access probability. This originates from their different frame sizes and traffic rates. According to Fig. 9, the successful medium access probability values for AC_1 and AC_2 intersect at 31 fps, 8.5 fps, 40 fps, and 11 fps, in Fig. 9 (a), (b), (c), and (d), respectively. At the beginning the probability for AC_1 is higher than that of AC_2, but higher priority aids AC_2 to have larger successful medium access probability than AC_1 upon heavier traffic in the network. The reason for slightly lower successful medium access probability for AC_2 nodes is the larger number of nodes which have AC_2 (6 nodes) but there are only 4 AC_1 nodes in the WBANs. When TXOP =0 the network performance is more affected by the noisy channel since it increases the medium contention. However, according to Fig. 10, higher AC priority for regular nodes results in higher successful medium access probability. This is because all traffic parameters are homogeneous for the regular WLAN nodes. The frame sizes, the frame arrival rates, and data frame error rates are equal for all ACs in the regular WLAN nodes.



(a) 3 regular nodes, TXOP=0 (b) 10 regular nodes, TXOP=0 (c) 3 regular nodes, TXOP=5000 μsec (d) 10 regular nodes, TXOP=5000 μsec

Fig. 9. Successful medium access probability for bridges in the WLAN with 3 and 10 regular WLAN nodes which have all four ACs. TXOP = 0 and TXOP =5000 μsec. BER = $2 * 10^{-5}$. There are 10 bridges in the WLAN.

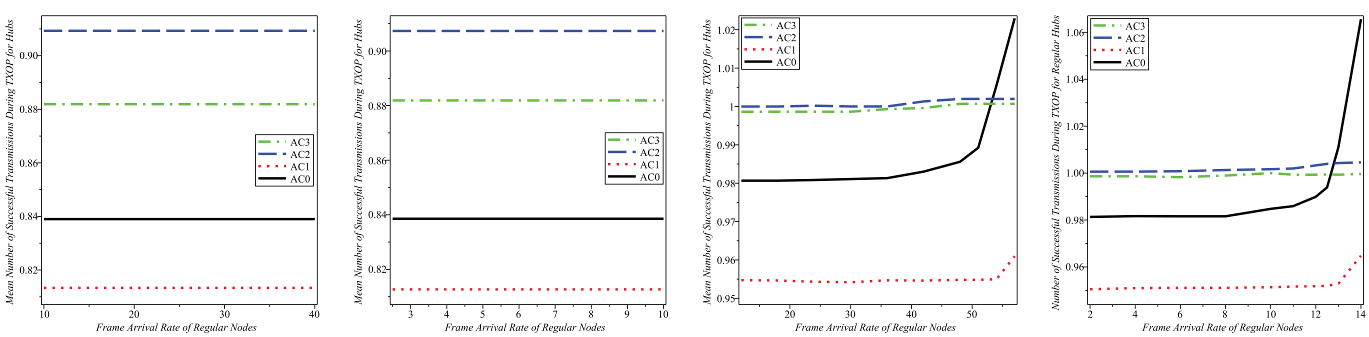
Fig. 11 represents the mean number of transmitted data frames during a TXOP access for bridges in the WLAN. When TXOP is equal to 0 the graphs show the successful transmission rate during the TXOP access. During a successfully obtained TXOP period only the error-prone channel may corrupt a transmitted frame. AC_2 (encapsulating WBAN UP_4 and UP_5 data frames) and AC_1 (including WBAN UP_2 and UP_3 data frames) have the highest and lowest successful transmission rates since their data frames on average are smallest (400 B) and largest (1100 B), respectively. In addition note that when TXOP=0, the number of regular nodes does not affect the mean number of successfully transmitted frames during the



(a) 3 regular nodes, TXOP=0 (b) 10 regular nodes, TXOP=0 (c) 3 regular nodes, TXOP=5000 μsec (d) 10 regular nodes, TXOP=5000 μsec

Fig. 10. Successful medium access probability for regular WLAN nodes in the WLAN with 3 and 10 regular WLAN nodes which have all four ACs. TXOP = 0 and TXOP =5000 μsec. BER = $2 * 10^{-5}$. There are 10 bridges in the WLAN.

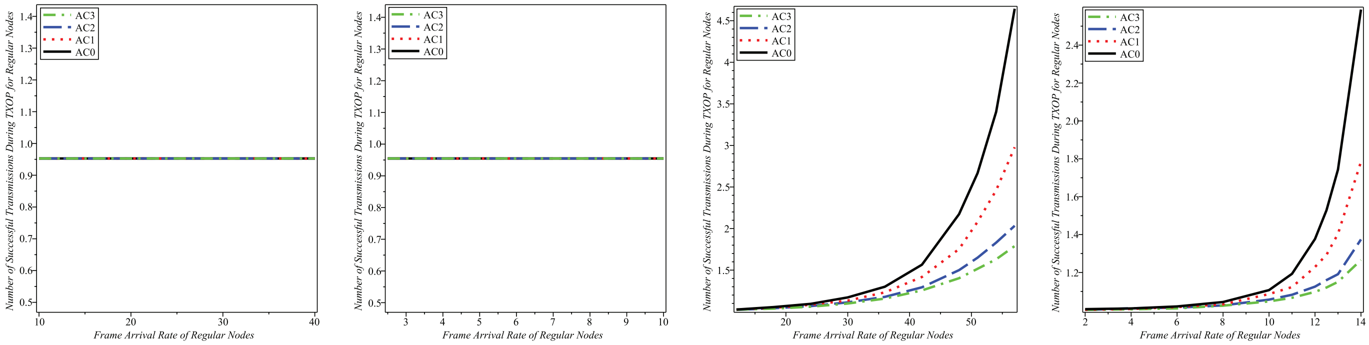
TXOP period. However, when TXOP=5000 μsec larger number of regular WLAN nodes causes larger number of transmissions by bridges during TXOP periods. When TXOP=5000 μsec, the nodes are able to transmit more than one data frame during the TXOP period if there is more data frames in the queue to be transmitted. When the traffic loads increase the probability of having more than one data frame in the queue at the instant of successful medium access increases. Hence, it is more likely that more than one data frame is transmitted by a node during the TXOP period.



(a) 3 regular nodes, TXOP=0 (b) 10 regular nodes, TXOP=0 (c) 3 regular nodes, TXOP=5000 μsec (d) 10 regular nodes, TXOP=5000 μsec

Fig. 11. Mean number of successfully transmitted frames during a TXOP access for hubs in the WLAN with 3 and 10 regular WLAN nodes which have all four ACs. TXOP = 0 and TXOP =5000 μsec. BER = $2 * 10^{-5}$. There are 10 bridges in the WLAN.

Fig. 12 shows the mean number of successfully transmitted data frames of regular WLAN nodes. As Fig. 12 (a) and (b) indicate the mean successful transmission rates for all ACs in the regular nodes are equal since the data frame sizes and BERs are equal for all the ACs. Fig. 12 (c) and (d) depict that when there are 3 regular WLAN nodes in the network with 51 fps as their arrival rates the AC_0, AC_1, AC_2, and AC_3 successfully transmit approximately 2.6, 2, 1.7, and 1.5 frames in the TXOP period, respectively. However, when there are 10 regular WLAN nodes generating 14 fps for each AC, AC_0, AC_1, AC_2, and AC_3 successfully transmit on average 2.6, 1.8, 1.4, and 1.3 frames in the TXOP period, respectively.

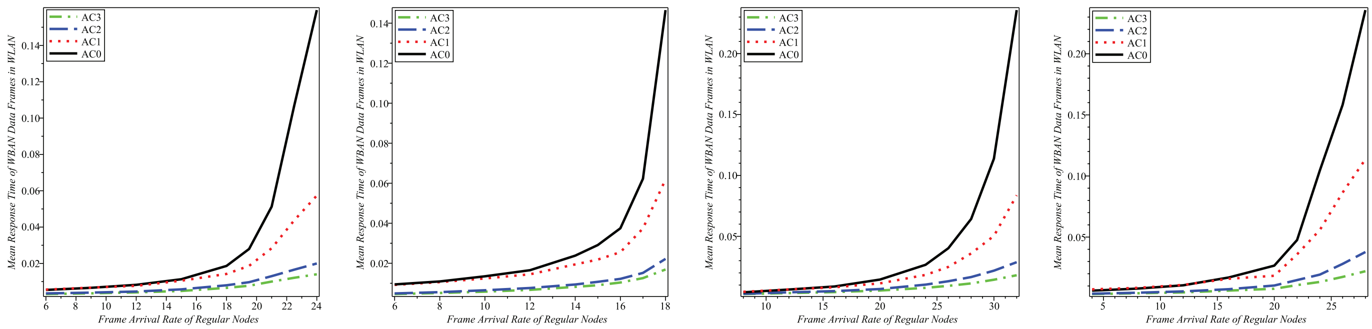


(a) 3 regular nodes, TXOP=0 (b) 10 regular nodes, TXOP=0 (c) 3 regular nodes, TXOP=5000 μsec (d) 10 regular nodes, TXOP=5000 μsec

Fig. 12. Mean number of successfully transmitted frames during a TXOP access for regular nodes in the WLAN with 3 and 10 regular WLAN nodes which have all four ACs. TXOP = 0 and TXOP =5000 μsec. BER = $2 * 10^{-5}$. There are 10 bridges in the WLAN.

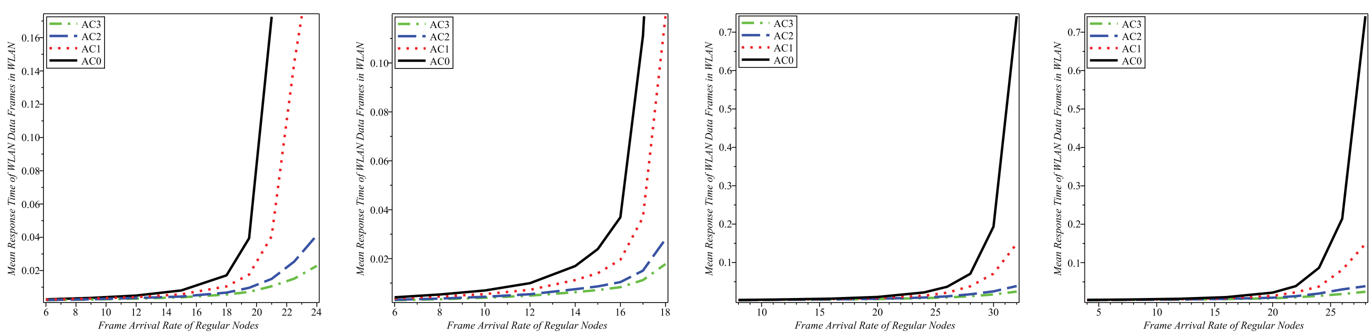
Impact of BER on the network performance

In the second set of experiments, we vary the channel quality by changing the BER value. We consider two cases of BER=$2 * 10^{-5}$ and BER=$5 * 10^{-5}$ where there are 5 regular WLAN nodes in the network. We evaluate the network performance when the TXOP value is set to 0 and 5000 μsec. The performance descriptors in this section indicate that BER noticeably affects the network performance. Fig. 13 and Fig. 14 show the data frame mean response times for bridges and regular WLAN nodes in the WLAN, respectively. Based on Fig. 13 (a) and (b) when TXOP=0, the assumed data frame response time tolerance threshold for the bridges' AC_0 (0.04 sec) is exceeded where the regular WLAN nodes generate 20 fps and 16 fps for BER=$2*10^{-5}$ and BER=$5*10^{-5}$, respectively. The same thing happens when TXOP=5000 μ sec, as indicated by Fig. 13 (c) and (d), increasing BER from $2*10^{-5}$ to $5*10^{-5}$ causes the decrease of approximately 5 fps (from 26 fps to 21 fps) to exceed the tolerance threshold (0.04 sec). BER growth increases the mean data frame response time for both bridges and regular WLAN nodes since the frames (including the control and data frames) error rate increases. This forces the nodes to attempt more retransmissions. Larger BER causes more retransmissions and results in much higher contention on the medium.



(a) 5 regular nodes, TXOP=0, BER=$2*10^{-5}$ (b) 5 regular nodes, TXOP=0, BER=$5*10^{-5}$ (c) 5 regular nodes, TXOP=5000 μsec, BER=$2*10^{-5}$ (d) 5 regular nodes, TXOP=5000 μsec, BER=$5*10^{-5}$

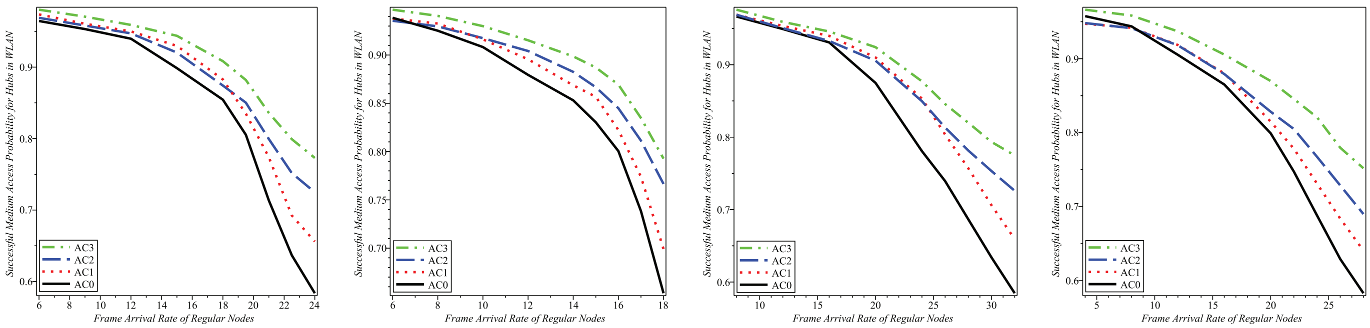
Fig. 13. Mean response time of aggregated WBAN data frames in the WLAN with 10 bridges and 5 regular WLAN nodes which have all four ACs, TXOP = 0 and TXOP =5000 μsec, BER = $2*10^{-5}$ and BER=$5*10^{-5}$.



(a) 5 regular nodes, TXOP=0, BER=$2*10^{-5}$ (b) 5 regular nodes, TXOP=0, BER=$5*10^{-5}$ (c) 5 regular nodes, TXOP=5000 μsec, BER=$2*10^{-5}$ (d) 5 regular nodes, TXOP=5000 μsec, BER=$5*10^{-5}$

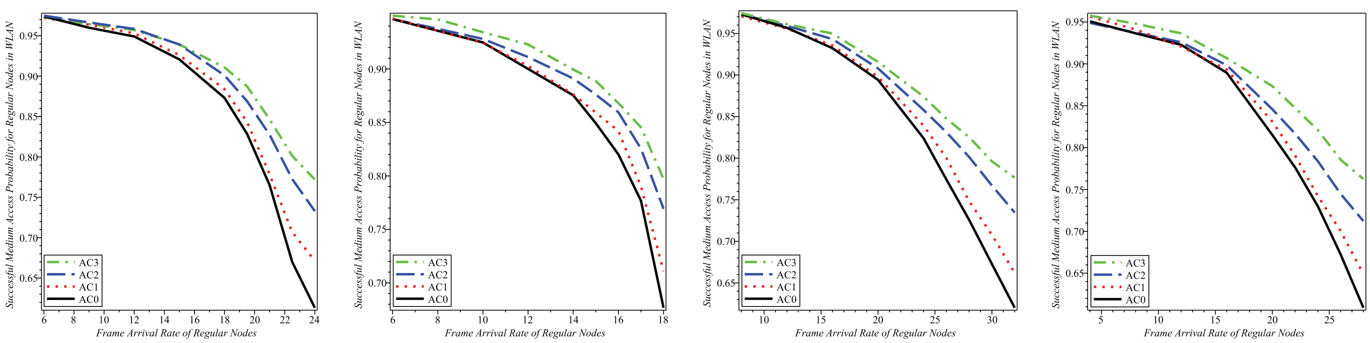
Fig. 14. Mean response time of WLAN data frames in the WLAN with 10 bridges and 5 regular WLAN nodes which have all four ACs, TXOP = 0 and TXOP =5000 μsec, BER = $2*10^{-5}$ and BER=$5*10^{-5}$.

Fig. 15 and Fig. 16 depict the successful medium access probability for bridges and regular WLAN nodes, respectively, for the cases when the BER is equal to $2*10^{-5}$ and $5*10^{-5}$. The results indicate that BER can have a large impact on the performance of the bridges. When TXOP=0, the successful medium access probability for AC_0 becomes equal to 0.65 at 22 fps and 18 fps (as the arrival rate of regular WLAN nodes), in case of BER=$2*10^{-5}$ and BER=$5*10^{-5}$, respectively. In addition, the plots indicate that setting larger TXOP values would improve the network performance in case of low channel quality.



(a) 5 regular nodes, TXOP=0, BER=$2 * 10^{-5}$ (b) 5 regular nodes, TXOP=0, BER=$5 * 10^{-5}$ (c) 5 regular nodes, TXOP=5000 μsec, BER=$2 * 10^{-5}$ (d) 5 regular nodes, TXOP=5000 μsec, BER=$5 * 10^{-5}$

Fig. 15. Successful medium access probability for bridges (hubs) in the WLAN with 10 bridges and 5 regular WLAN nodes which have all four ACs, TXOP = 0 and TXOP =5000 μsec, BER = $2 * 10^{-5}$ and BER=$5 * 10^{-5}$.



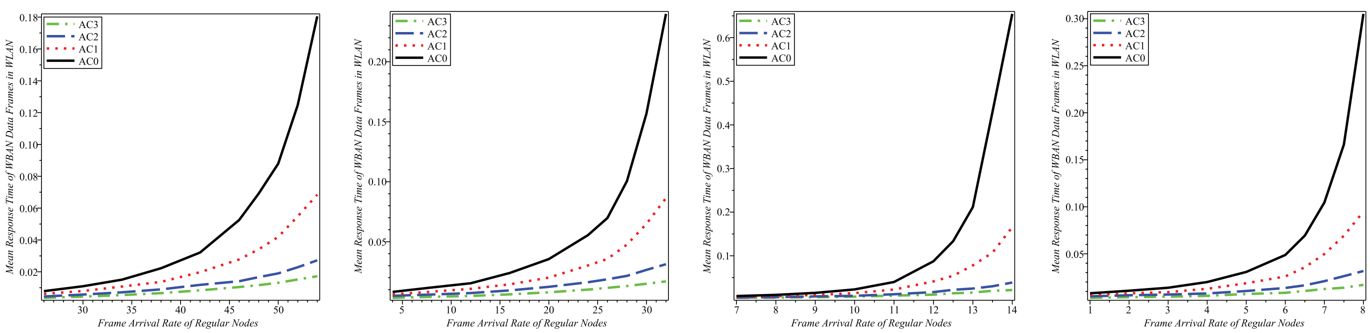
(a) 5 regular nodes, TXOP=0, BER=$2 * 10^{-5}$ (b) 5 regular nodes, TXOP=0, BER=$5 * 10^{-5}$ (c) 5 regular nodes, TXOP=5000 μsec, BER=$2 * 10^{-5}$ (d) 5 regular nodes, TXOP=5000 μsec, BER=$5 * 10^{-5}$

Fig. 16. Successful medium access probability for regular nodes in the WLAN with 10 bridges and 5 regular WLAN nodes which have all four ACs, TXOP = 0 and TXOP =5000 μsec, BER = $2 * 10^{-5}$ and BER=$5 * 10^{-5}$.

B. Transferring WBAN data frames without aggregation to the WLAN access point

In the second scenario, the bridges transmit individual WBAN data frames to the WLAN access point. Compared to the previous scenario, in which every aggregated data frame encapsulated four WBAN data frames to the same AC, the data frame sizes in the second scenario are smaller. However, the bridges in the second scenario have lager numbers of data frames to transmit to the server. In all experiments in this section, TXOP values are set to 5000 μsec for all ACs and BER is set to $2 * 10^{-5}$. Frame arrival rates for regular WLAN nodes are exponentially distributed.

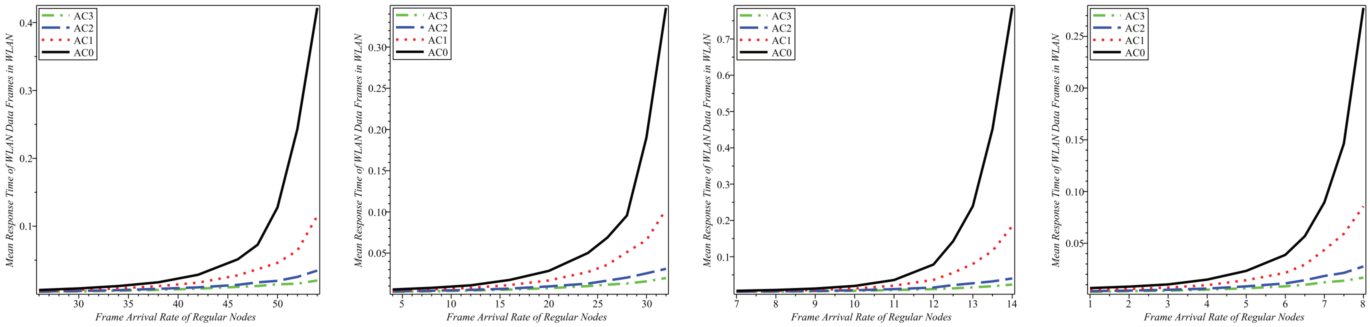
Fig. 17 (a) and (b) show the mean response time of the data frames generated by the bridges where the number of the bridges in the network is set to 5 and 10, while there are 3 regular WLAN nodes. Increasing the number of WBANs in an area also considerably affects the network performance as the bridges leave the linear region at 42 fps and 20 fps (as the arrival rate of regular WLAN nodes) where there are 5 and 10 WBANs in the network, respectively. Fig. 17 (c) and (d) represent the results when there are 10 regular WLAN nodes in the network. The results indicate that for having a stable network and acceptable WBAN data frame response time the number of both WBANs and regular WLAN nodes in the network must be controlled. Admission control mechanisms should be performed to preserve both WBANs and regular WLAN nodes in stable condition. Fig. 18 shows the mean response time of data frames for regular WLAN nodes. The results indicate the large impact of the number of WBANs on the performance of the other nodes in the network.



(a) 5 bridges, 3 regular nodes (b) 10 bridges, 3 regular nodes (c) 5 bridges, 10 regular nodes (d) 10 bridges, 10 regular nodes

Fig. 17. Mean response time of WBAN data frames in the WLAN. 5 and 10 bridges (WBANs), 3 and 10 regular WLAN nodes which have all four ACs, TXOP =5000 μsec, BER = $2 * 10^{-5}$.

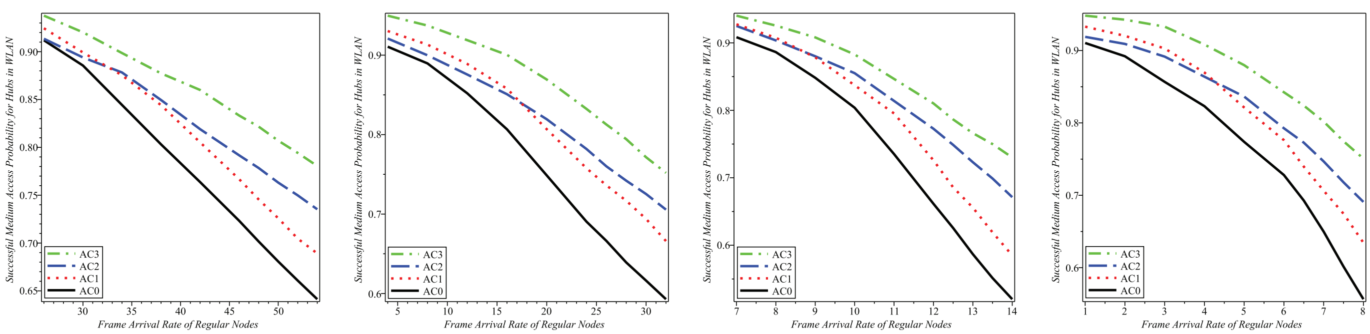
Fig. 19 and Fig. 20 show the successful medium access probability for the bridges and the regular WLAN nodes, respectively. The results indicate that having 10 hubs and 10 regular nodes in the network, when the bridges do not aggregate the WBAN data frames, causes a high contention on the medium. Arrival rate of only 8 fps for regular WLAN nodes results in successful medium access probability of lower than 60%. Fig. 21 and Fig. 22 show the mean number of successfully transmitted frames during the TXOP access when every WBAN data frame is individually transmitted. Fig. 21 indicates that the plots of AC_1 and AC_2 intersect at some point. At the beginning AC_1 transmits lower number of frames in



(a) 5 bridges, 3 regular nodes (b) 10 bridges, 3 regular nodes (c) 5 bridges, 10 regular nodes (d) 10 bridges, 10 regular nodes

Fig. 18. Mean response time of WLAN data frames in the WLAN. 5 and 10 bridges (WBANs), 3 and 10 regular WLAN nodes which have all four ACs, TXOP =5000 μsec, BER = $2 * 10^{-5}$.

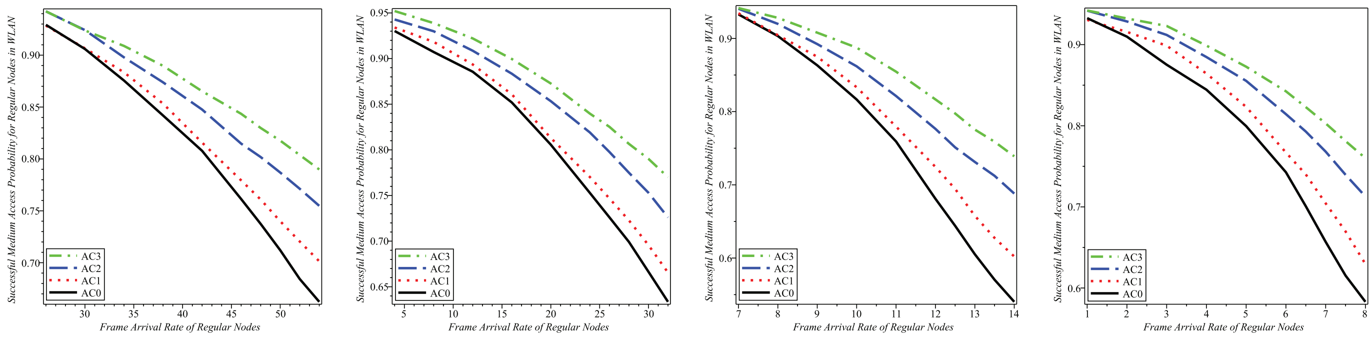
the TXOP periods while later on AC_2 transmits smaller number of data frames. The reason is the larger number of nodes with AC_2 than the number of nodes with AC_1. However, when the traffic rates of the regular WLAN nodes increase, which results in higher contention on the medium, higher priority aids AC_2 to transmit lower number of data frames during the TXOP periods compared to AC_1.



(a) 5 bridges, 3 regular nodes (b) 10 bridges, 3 regular nodes (c) 5 bridges, 10 regular nodes (d) 10 bridges, 10 regular nodes

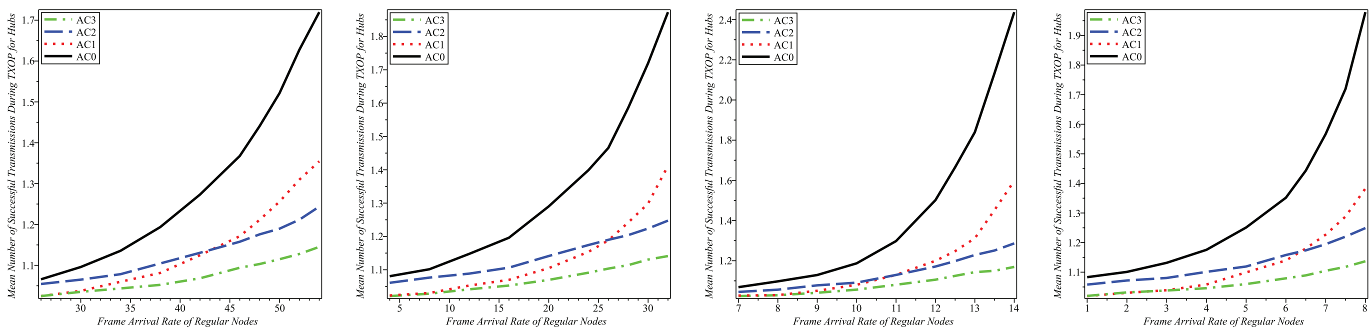
Fig. 19. Successful medium access probability for bridges in the WLAN. 5 and 10 bridges (WBANs), 3 and 10 regular WLAN nodes which have all four ACs, TXOP =5000 μsec, BER = $2 * 10^{-5}$.

In the last experiment, we investigate the network performance where there are only 10 bridges in the network without any regular WLAN nodes. Fig. 23 (a) shows the the mean response time of WBAN data frame from the moment they are generated in the bridge until the moment when they are successfully transmitted. The plot indicates that increasing the RAP length as a WBAN parameter does not considerably affect the performance of the hubs in the WLAN. The data frame size is another parameter that affects the data frames response time. Fig. 23 (b) depicts the mean successful medium access probability for bridges



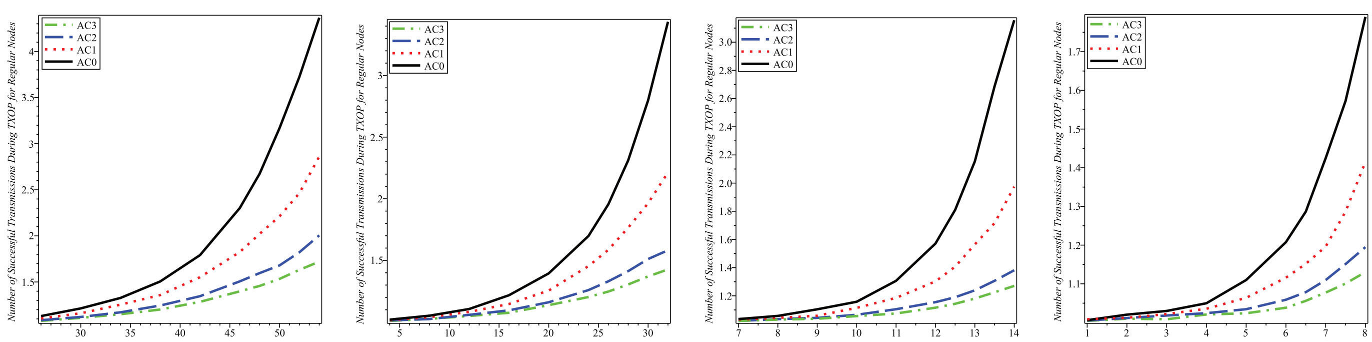
(a) 5 bridges, 3 regular nodes (b) 10 bridges, 3 regular nodes (c) 5 bridges, 10 regular nodes (d) 10 bridges, 10 regular nodes

Fig. 20. Successful medium access probability for regular WLAN nodes in the WLAN. 5 and 10 bridges (WBANs), 3 and 10 regular WLAN nodes which have all four ACs, TXOP =5000 μsec, BER = $2 * 10^{-5}$.



(a) 5 bridges, 3 regular nodes (b) 10 bridges, 3 regular nodes (c) 5 bridges, 10 regular nodes (d) 10 bridges, 10 regular nodes

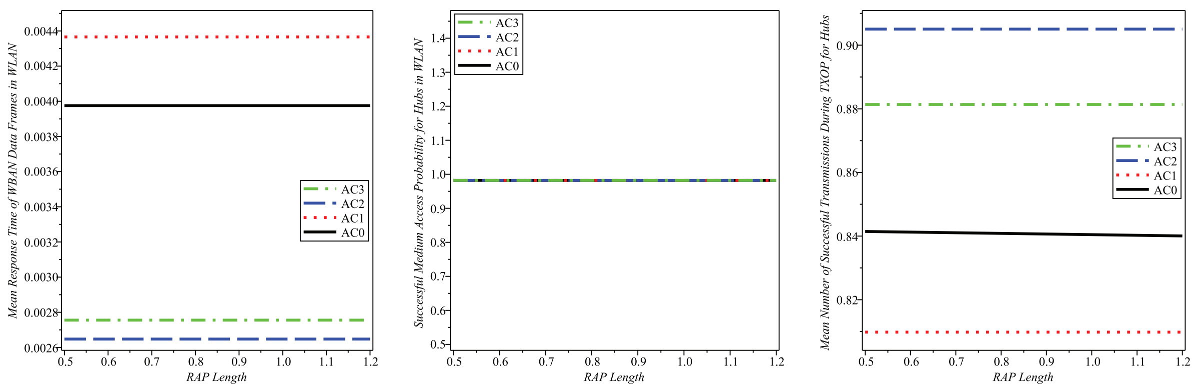
Fig. 21. Mean number of successfully transmitted frames during a TXOP access for bridges in the WLAN. 5 and 10 bridges (WBANs), 3 and 10 regular WLAN nodes which have all four ACs, TXOP =5000 μsec, BER = $2 * 10^{-5}$.



(a) 5 bridges, 3 regular nodes (b) 10 bridges, 3 regular nodes (c) 5 bridges, 10 regular nodes (d) 10 bridges, 10 regular nodes

Fig. 22. Mean number of successfully transmitted frames during a TXOP access for regular WLAN nodes in the WLAN. 5 and 10 bridges (WBANs), 3 and 10 regular WLAN nodes which have all four ACs, TXOP =5000 μsec, BER = $2 * 10^{-5}$.

in the network. The figure indicates when the traffic load is low the successful medium access rate is almost equal for all the ACs. Finally, Fig. 23 (c) shows the mean number of successful transmissions during the TXOP periods for bridges. According to the results, the larger the data frame size is the more transmission attempts are required since the frames are more likely corrupted by noise. It might also cause a smaller number of transmissions during the TXOP periods if the TXOP period has a non-zero value.



(a) Mean Response Time of WBAN Data Frames in WLAN

(b) Successful Medium Access Probability for Bridges in WLAN

(c) Mean Number of Successful Transmissions During TXOP for Bridges

Fig. 23. Performance descriptors in case there are only bridges in the WLAN. 10 bridges (WBANs), TXOP =0, BER = $2 * 10^{-5}$.

V. Conclusion

In this paper, we investigated the MAC performance of a healthcare network implemented by bridging WBANs and a WLAN. We developed a prioritized bridging mechanism between IEEE 802.15.6-based WBANs and an IEEE 802.11e EDCA-based WLAN considering all 8 UPs in the WBAN and all 4 ACs in the WLAN. In order to have moderate differentiation and lower frame collision probability we deployed AIFS for differentiating the WLAN ACs. We provided an extensive set of simulation experiments to study the impacts of a variety of network and MAC prioritizing parameters on the two-hop network performance. We present performance descriptors including the mean data frame response time, the successful medium access probability, the mean number of successful transmissions during TXOP accesses and the successful transmission rate. The results of this work indicate that judicious choice of MAC parameters considerably improves the performance of all WLAN ACs and as the result the network performance. The results also indicate that not only the number of WBANs but also the number of regular WLAN nodes have a large impact on the healthcare network performance. Hence, admission control mechanisms for regular WLAN nodes should be performed to satisfy the required performance bounds of the healthcare network and the regular nodes.

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