This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JBHI.2014.2387867, IEEE Journal of Biomedical and Health Informatics

Coexistence of ZigBee-based WBAN and WiFi for Health Telemonitoring Systems

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***Abstract*—The development of telemonitoring via wireless body area networks (WBANs) is an evolving direction in personalized medicine and home-based mobile health. A WBAN consists of small, intelligent medical sensors which collect physiological parameters such as EKG (electrocardiogram), EEG (electroencephalography) and blood pressure. The recorded physiological signals are sent to a coordinator via wireless technologies, and are then transmitted to a healthcare monitoring center. One of the most widely used wireless technologies in WBANs is ZigBee because it is targeted at applications that require a low data rate and long battery life. However, ZigBee-based WBANs face severe interference problems in the presence of WiFi networks. This problem is caused by the fact that most ZigBee channels overlap with WiFi channels, severely affecting the ability of healthcare monitoring systems to guarantee reliable delivery of physiological signals. To solve this problem, we have developed an algorithm that controls the load in WiFi networks to guarantee the delay requirement for physiological signals, especially for emergency messages, in environments with coexistence of ZigBee-based WBAN and WiFi. Since WiFi applications generate traffic with different delay requirements, we focus only on WiFi traffic that does not have stringent timing requirements. In this paper, therefore, we propose an adaptive load control algorithm for ZigBee-based WBAN/WiFi coexistence environments, with the aim of guaranteeing that the delay experienced by ZigBee sensors does not exceed a maximally tolerable period of time. Simulation results show that our proposed algorithm guarantees the delay performance of ZigBee-based WBANs by mitigating the effects of WiFi interference in various scenarios.**

***Index Terms*—Wireless body area network, ZigBee, health telemonitoring, adaptive load control, delay**

I. Introduction

The development of health telemonitoring via wireless body area networks (WBANs) is an evolving direction in personalized medicine and home-based mobile health. In a health telemonitoring system, a WBAN consists of a number of lightweight miniature sensors. The sensors measure physiological parameters such as electrocardiography (EKG), electroencephalogram (EEG), body temperature and blood pressure. These measurements are transmitted to an external data aggregation device called a coordinator via wireless communication networks, and are then sent to a health telemonitoring center (e.g., a hospital) via the Internet. At the hospital, medical professionals monitor their patients' physiological parameters continuously, so that there is no need for them to visit the hospital in person.

The physiological signals in the system can be categorized into two types: regularly collected information and emergency messages. Regularly collected information is stored and transmitted after a given period of time, while emergency messages must be transmitted immediately since they alert the hospital to emergency situations such as excessively high or low blood pressure or body temperature, or heart beat stoppage. According to the TG6 Technical Requirement Document (TRD), emergency messages must be transmitted in less than 1 sec [1]. Hence, guaranteed delay requirement is of utmost importance to the proper operation of health telemonitoring systems.

One of the most widely used wireless technologies in WBANs is ZigBee (IEEE 802.15.4) because "it is targeted at applications that require a low data rate and long battery life" [2]. However, operating on the unlicensed 2.4 GHz industrial scientific and medical (ISM) band, ZigBee is subject to interference from coexisting WiFi (IEEE 802.11) devices which share this band. This is because the transmit power of WiFi is 5-20 dB stronger than that of ZigBee, which "easily forces ZigBee sensors to back off and dominate the ZigBee interference" [3]. In the presence of WiFi devices, therefore, it is difficult to guarantee reliable delivery of vital signs, especially for emergency messages. Furthermore, "with the proliferation of WiFi devices (e.g., smartphones) and high-rate applications (e.g., HD video streaming)," recent studies have shown that "moderate to high WiFi traffic" increases the delivery delay of each ZigBee packet [3].

In recent years, extensive efforts [4]-[14] have been made to enhance the performance of ZigBee in coexistence environments. To avoid WiFi interference, the authors in [4]-[6] propose channel allocation algorithms that assign channels which are less frequently used or unused by WiFi devices to ZigBee sensors. This is a simple method, but it results in providing only a limited number of channels for ZigBee sensors in densely deployed WiFi environments. To avoid this problem, the authors in [3][7] propose interference mitigation algorithms that are applied when ZigBee and WiFi devices operate on the same channels. However, it is hard to apply these algorithms to WBANs for health telemonitoring systems since they do not take into account WBAN features such as star topology, low delay requirement, and patient mobility. Although the authors in [8]-[11] consider coexistence of ZigBee-based WBANs and WiFi devices for health telemonitoring, none of them specifies a solution to the interference problem. Recently, the authors in [12]-[14] have proposed schemes for the reliable transmission of medical data. While the authors in

Manuscript received XX;revised XX; accepted XX.

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This research was supported by the MSIP (Ministry of Science, ICT and Future Planning), Korea, under the ITRC (Information Technology Research Center) support program (NIPA-2014-H0301-14-1042) supervised by the NIPA (National IT Industry Promotion Agency).

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[12] neglect to consider the problem of interference between different wireless technologies, the authors in [13] and [14] address this problem by "extracting idle spaces from a group of orthogonal candidate channels" and assigning the extracted channels to target sensors. However, this process results in the same problems that arise from the channel allocation algorithms (i.e., additional delay and limited number of channels). Therefore, there exists a pressing need to devise a new scheme that guarantees the delay requirement for health telemonitoring systems, especially for emergency messages, in ZigBee-based WBAN and WiFi coexistence environments.

We propose an algorithm that satisfies the delay requirement for emergency messages by controlling WiFi traffic for health telemonitoring systems. In WiFi networks, various WiFi applications such as WWW, FTP, P2P, and audio/video streaming generate traffic with different delay requirements. For example, delays for video traffic from PPLive should not exceed 400 ms, whereas 5 s is suggested as an acceptable delay for data traffic from BitTorrent [15][16]. Hence, in this paper, we control only WiFi traffic that is not stringently delay-sensitive.

The rest of this paper is organized as follows. Section II summarizes previous work related to the interference problem. Section III presents analytical models of the PER in WiFi networks and delays in ZigBee-based WBANs, and describes our adaptive load control algorithm. In Section IV, we report the results of simulation experiments that demonstrate the performance improvements of the proposed algorithm. Finally, we conclude the paper in Section V.

II. Related Work

There have been many studies on minimizing WiFi interference by allocating channels that are less frequently used or unused by WiFi devices to ZigBee sensors. Zhao *et al.* propose "a multi-radio testbed" for heterogeneous wireless sensor networks [4]. They use the testbed to study the coexistence problem of IEEE 802.15.4 and IEEE 802.11. Based on their evaluation results, "guidelines on channel allocation and network parameter" configurations are offered to minimize interference. Won *et al.* propose an "adaptive channel allocation scheme" for supporting the coexistence of 802.15.4 and 802.11b, allowing 802.15.4 to utilize multiple channels in a wireless personal area network (WPAN) [5]. Yet the scheme is impractical since each WPAN is assumed to use only one channel. Yi *et al.* propose "a frequency agility-based interference avoidance algorithm" in which once interference is detected, "the coordinator selects the channel with the lowest noise levels and then requests all nodes in the PAN to migrate to this channel" [6]. Based on their simulation results, they suggest a "safe distance and safe offset frequency to guide ZigBee deployment" in the presence of WiFi interference. However, it is not easy to maintain their recommended "safe distance and safe offset frequency" due to the movement of WiFi users. Although the channel allocation algorithms provide a straightforward way to avoid WiFi interference, there are still delays in detecting interference and changing operating channels [4]-[6]. Furthermore, there are only a limited number of channels for ZigBee sensors in densely deployed WiFi environments. Therefore, an interference mitigation algorithm is needed when ZigBee and WiFi operate on the same channel.

To avoid WiFi interference at the coordinator due to the higher signal strength of WiFi than of ZigBee and to the use of the same channel as ZigBee, some approaches have been proposed based on particular characteristics of ZigBee and WiFi [3][7]. Kim *et al.* present an interference-aware topology control algorithm for low-rate WPANs in which "each WPAN node estimates interference effects periodically and re-constructs the network topology when interference is detected" [7]. Their evaluation results demonstrate the effectiveness of the proposed algorithm in wide areas with numerous nodes. Zhang *et al.* propose "cooperative carrier signaling (CCS)" to facilitate coexistence between ZigBee and WiFi [3]. "CCS employs a separate ZigBee node to emit a carrier signal (a busy tone) concurrently with the desired ZigBee data transmission," thereby "enhancing the visibility of ZigBee to WiFi" [3]. Despite the clear advantages of the interference mitigation methods described above, they are difficult to apply to ZigBee-based WBANs for health telemonitoring systems because they do not take into account particular WBAN features as follows. First, the effectiveness of the algorithm proposed in [7] is not guaranteed in WBANs consisting of only a few sensors that are directly connected to a coordinator. Second, the additional ZigBee device needed in [3] to emit a busy tone has to be attached onto a patient's body.

Coexistence architectures for health telemonitoring have been proposed in [8]-[11]. Francisco *et al.* present a coexistence structure and evaluate "the feasibility of WBAN systems" in hospital rooms, assessing their robustness to WiFi interference [8]. They conclude that in the presence of 802.11g interference within the room, an 802.15.4 link cannot ensure high performance even for large frequency offsets due to close reflections from the walls. However, they do not provide any explanation of how to minimize WLAN interference in hospital rooms. In [9]-[11], the authors develop a two-tier wireless architecture that uses WBAN and WLAN for health telemonitoring. The authors in [9] and [10] introduce a "two-tier networking structure that uses IEEE 802.15.4 low data-rate WPAN for the patient's BAN, and IEEE 802.11b for the connection between the BAN coordinators and the wired portion of the healthcare system." Rashwand *et al.* develop the architecture of an "IEEE 802.15.6-based WBANs/IEEE 802.11e enhanced distributed channel access (EDCA)-based" WLAN bridged network for a wireless healthcare system [11]. By mapping the "WBAN user priorities into WLAN access categories," they convey the medical data to the WLAN AP. Despite the fact that the authors in [9]-[11] propose the two-tier architectures using IEEE 802.15.4 and IEEE 802.11 for healthcare monitoring, they assume no interference between them.

"Due to potentially life-threatening situations, the reliable and timely delivery of vital body parameters" is critically important for the effective operation of patient monitoring networks [12][14]. Although the authors in [12] propose a scheme for making IEEE 802.15.4-based WBANs able to pro-

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vide reliability in the transmission of health monitoring data, they consider only the interference caused by the transmissions of coexisting WBANs. Considering the interference between different types of wireless technologies, Torabi *et al*. propose "centralized body area network access scheme (CBAS)" in which a gateway extracts white spaces from the ISM band and Ultra Wideband (UWB) and then assigns them to sensors for health monitoring [13]. Using CBAS, Torabi *et al*. improve the packet delivery ratios for medical data transmissions [14]. Although these studies provide reliable transmissions over BANs [13][14], there are delays in changing channels. Even in an emergency situation, the sensor must first send a request to the gateway in order to obtain an opportunity to transmit.

Based on the above observations, we propose a new mechanism to guarantee the delay requirement for emergency messages with the aim of facilitating the coexistence of ZigBee-based WBANs and WiFi for healthcare monitoring systems. The main contributions of this paper are twofold:

- an adaptive load control algorithm for interference mitigation that controls only WiFi traffic generated from delay-tolerant applications; and
- guaranteed the maximum tolerable delay requirement for ZigBee-based WBANs, especially for emergency messages.

III. Adaptive Load Control for ZigBee-based WBANs with Coexisting WiFi Networks

In this section, we describe our proposed interference mitigation algorithm for regulating the load in WiFi networks to satisfy the delay requirement for ZigBee-based WBANs.

A. ZigBee-based WBAN/WiFi Coexistence Architecture

In this subsection, we present the ZigBee-based WBAN architecture with a coexisting WiFi network. In the architecture considered in this paper, the ZigBee-based WBAN coexists with a WiFi network at home. This is because WiFi networks are becoming increasingly popular as the number of mobile users who install small-size APs rises. Medical sensors, attached onto or implanted in the body, are connected to a coordinator via ZigBee communication. The coordinator, implemented on a personal digital assistant (PDA), cell phone, or personal computer (PC), aggregates medical information from ZigBee sensors and forwards the collected information to a health telemonitoring system through an access point (AP), which is connected to the Internet.

As mentioned in Section I, the goal of the health telemonitoring system is to provide automatic and reliable data transmission between the medical sensors and the health telemonitoring system. In the presence of WiFi traffic on the shared channel, however, ZigBee-based WBANs can suffer significant degradation in delay performance due to WiFi interference. In such cases, it is difficult to guarantee fast transmission of an emergency message when an emergency condition (e.g., heart attack) has been detected.

Some applications in WiFi networks generate traffic that does not have stringent timing requirements. For example, while 5 s is an acceptable delivery delay for data traffic from

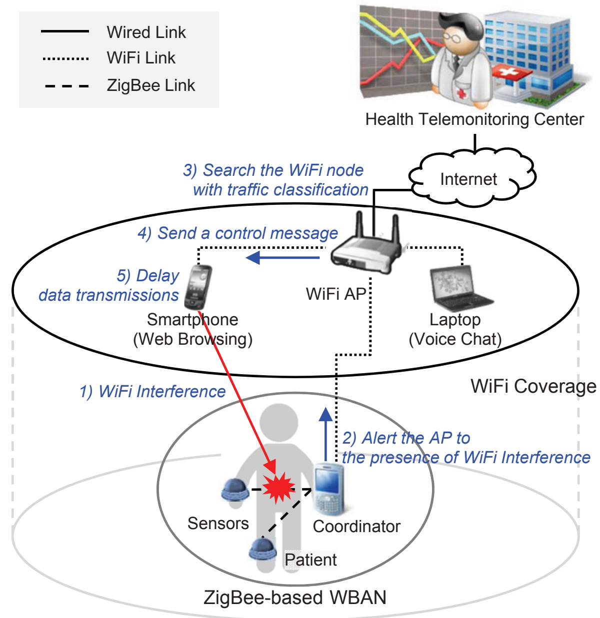

Fig. 1: The overall ZigBee-based WBAN architecture coexisting with WiFi.

BitTorrent, the latency of video traffic from PPLive should be less than 400 ms [15][16]. In this paper, therefore, we propose an algorithm for reducing only the WiFi traffic generated from delay-tolerant applications to guarantee that delays experienced by ZigBee sensors, especially for emergency messages, do not exceed the maximally tolerable delay.

The ZigBee-based WBAN/WiFi architecture is shown in Fig. 1. Once interference is detected, the coordinator sends the WiFi node information to alert the AP to the presence of WiFi interference. The AP identifies the WiFi node that has the highest received signal strength and is generating traffic that does not have any time-based sensitivity requirements. With the use of traffic classification, the traffic has already been determined. The AP then sends a message to the identified WiFi node, and upon its receipt, the node reduces its transmission rate.

B. PER Analysis in ZigBee-based WBAN/WiFi Coexistence Networks

For WiFi networks, let P_{cca} be the clear channel assessment (CCA) power threshold in watts. This is the minimum power required for correct receipt of transmitted packets. We define $A_c^{(w)}$ as a set of WiFi nodes whose signal strength observed at a coordinator c is greater than P_{cca}:

$$A_c^{(w)} = \{\text{WiFi node } j \mid P_{c,j}^{(w)} \geq P_{cca}\}, \tag{1}$$

where $P_{c,j}^{(w)}$ is the received signal power of WiFi node j observed at coordinator c. Let $P_{c,m}$ be the power of the signal sent from ZigBee sensor m at ZigBee coordinator c's receiver, and let P_{noise} be the received noise power level at coordinator c. The signal-to-interference-plus-noise ratio (SINR) at coordinator c from ZigBee sensor m with WiFi

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interference, $S^{(I)}_{c,m}$, and without WiFi interference, $S_{c,m}$, are given as

$$S^{(I)}_{c,m} = \frac{P_{c,m}}{P_{noise} + P^{(w)}_c} \tag{2}$$

and

$$S_{c,m} = \frac{P_{c,m}}{P_{noise}}, \tag{3}$$

where $P^{(w)}_c$ is the average received signal power of WiFi nodes observed at coordinator c.

Assuming an additive white Gaussian noise (AWGN) channel, we can express the bit error rate (BER) as a function of the SINR as follows [6][17]:

$$BER(S) = Q(\sqrt{2\gamma S}), \tag{4}$$

where $\gamma = 0.85$ and $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty exp\left(-\frac{y^2}{2}\right) dy$.

Using Eqs. (2)-(4), the packet error rate (PER) for a packet sent from ZigBee sensor m when coordinator c receives a packet is determined as follows:

$$e_{c,m} = 1-(1-BER(S_{c,m}))^{L(1-u^{(w)}_c)} \times (1-BER(S^{(I)}_{c,m}))^{Lu^{(w)}_c}, \tag{5}$$

where L is the average length of a ZigBee packet and $u^{(w)}_c$ is the WiFi channel utilization observed at coordinator c.

C. Delay Analysis in ZigBee-based WBANs

Let T_{bi} and T_{sf} denote the beacon interval and the superframe duration in the ZigBee network, respectively. Noting that each packet is generated in a slot, the average waiting time before sensing the channel condition (i.e., CCA) is

$$D_{wt} = \frac{T_{bi} - T_{sf}}{T_{bi}} \frac{T_{bi} - T_{sf}}{2} = \frac{(T_{bi} - T_{sf})^2}{2T_{bi}} \tag{6}$$

The ZigBee node waits for a random number of backoff periods and senses the channel condition. The random number for backoff is uniformly distributed in the range of $[0, W_0 - 1]$, where W_0 is the size of the initial contention window. If the channel is busy, channel access fails and the ZigBee sensor waits again for a random number of backoff periods with the new contention window $W_1 = 2 \times W_0$. Subsequent channel access failure causes further doublings of the contention window until the window size reaches a maximum value of W_X. Thus, the average backoff time for the contention window size W_x $(0 \leq x \leq X)$ can be expressed as

$$\begin{aligned} D^{(b)}_x &= \frac{W_x + 1}{2} T_b + (T_{bi} - T_{sf}) \sum_{k=1}^{W_x} \frac{k}{N_{sf} W_x} \\ &= \frac{W_x + 1}{2} (T_b + \frac{1}{N_{sf}} (T_{bi} - T_{sf})), \end{aligned} \tag{7}$$

where T_b is the duration of backoff of a ZigBee whose length is 20 symbol periods ($= 320\mu s$) and $N_{sf} = T_{sf}/T_b$ is the number of backoff periods in a superframe.

Let $u^{(z)}_c$ be the ZigBee channel utilization observed at coordinator c. By using Eqs. (6) and (7), we can obtain the average backoff time for a ZigBee packet sent from ZigBee sensor m to coordinator c as follows:

$$\begin{aligned} D^{(b)}_{c,m} =& D_{wt} + (u^{(z)}_c)^0 D^{(b)}_0 + ... \\ &+ (u^{(z)}_c)^{X-1} D^{(b)}_{X-1} + \frac{(u^{(z)}_c)^X}{1 - u^{(z)}_c} D^{(b)}_X \\ =& D_{wt} + \sum_{x=1}^{X-1} (u^{(z)}_c)^x D^{(b)}_x + \frac{(u^{(z)}_c)^X}{1 - u^{(z)}_c} D^{(b)}_X. \end{aligned} \tag{8}$$

Let T_s and T_f be the duration of successful and unsuccessful ZigBee frame transmissions, respectively. For IEEE 802.15.4, $T_s = bL + T_{CCA} + T_{SIFS} + T_{ACK}$ and $T_f = bL + T_{CCA} + T_{ACK,TO}$, where b is the duration of a bit transmission, T_{CCA} is the duration of CCA in ZigBee, T_{SIFS} is the duration of a short ZigBee interframe space, T_{ACK} is the duration of a ZigBee ACK packet, and $T_{ACK,TO}$ is the duration of ZigBee ACK timeout [6]. Using Eqs. (5) and (8), we can obtain the transmission delay $D_{c,m}$ for a ZigBee packet sent from ZigBee sensor m to coordinator c, as follows:

$$\begin{aligned} D_{c,m} &= (D^{(b)}_{c,m} + T_s) + \frac{e_{c,m}}{1 - e_{c,m}} (D^{(b)}_{c,m} + T_f) \\ &= T_s + (1 - e_{c,m})^{-1} (D^{(b)}_{c,m} + e_{c,m} T_f). \end{aligned} \tag{9}$$

D. WiFi Traffic Classification

We aim to improve the delay performance of the ZigBee network by controlling only the WiFi traffic generated from delay-tolerant applications so that delay-sensitive WiFi traffic remains uninterrupted. In this subsection, therefore, we introduce a mechanism that classifies WiFi traffic into the two classes of real-time (RT) (e.g., PPLive, Google Hangouts) and non-real-time (NRT) (e.g., BitTorrent, Web Browsing, YouTube) and identifies the traffic class for an application.

Our classification mechanism works in two phases: offline training and online classification phases. In the offline training phase, we extract the characteristic features of the traffic generated by each application using Wireshark [18]. The features of the traffic we consider in this study are frame size (FS) and frame inter-arrival time (FIT). 50 % of the dataset is chosen randomly as the training dataset, and the remaining 50 % is used for testing [19]. The training phase calculates the statistical features of a set of training data (i.e., FS and FIT) and outputs a set of traffic descriptors $\{(FS_i, FIT_i)\}$ for the two classes. Then, when WiFi traffic arrives at the AP, it is identified online as one of the traffic classes using the statistical features obtained from the offline training phase.

E. Adaptive Load Control Algorithm for Guaranteeing Delay Requirements in ZigBee-based WBANs

In this subsection, we propose an adaptive load control algorithm to guarantee that the delay between a ZigBee sensor and a coordinator is no longer than the maximally tolerable delay $D_{\max}$ by using the analyses and traffic classification presented above. To detect WiFi interference, we first compute the PER of a packet sent from ZigBee sensor m to coordinator

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Algorithm 1 The guarantee of the delay requirement in a ZigBee Coordinator

$N_c = 1$, $u_c^{(w)} = 0$, $BUSY = false$, $t_D = 0$
while ($BUSY$ is $false$) or (Current_time() $< t_D$) **do**
  The coordinator monitors the channel to get $u_c^{(w)}$
  if $BUSY$ is $false$ **then**
    if $u_c^{(w)} > \tilde{u}_c$ **then**
      $BUSY = true$
      $t_D =$ Current_time() $+ D_z^{max}$
      $sum = u_c^{(w)}$
      $N_c = 1$
    end if
  else
    $N_c = N_c + 1$
    $sum = sum + u_c^{(w)}$
    if $(sum/N_c) < \tilde{u}_c$ **then**
      $BUSY = false$
    end if
  end if
end while
Send $\tilde{u}_c$ and the MAC address list of the WiFi nodes $\in A_c^{(w)}$ sorted in descending order of their $P_{c,j}^{(w)}$ to the AP

c to satisfy $D_{\max}$. Setting W_0 = 8 and X = 2 according to [2], Eq. (8) can then be rewritten as:

$$D_{c,m}^{(b)} = D_{wt} + \left(T_b + \frac{T_{bi} - T_{sf}}{N_{sf}}\right) \times \left(\frac{9}{2} + \frac{17}{2}u_c^{(z)} + \frac{33}{2}\left(\frac{(u_c^{(z)})^2}{1 - u_c^{(z)}}\right)\right). \tag{10}$$

The constraint for the maximum ZigBee delay, $D_{\max}$, is

$$D_{\max} \geq D_{c,m}, \quad \forall m \in A_c^{(z)}, \tag{11}$$

where $A_c^{(z)}$ is a set of ZigBee nodes connected to coordinator c. Eqs. (9) - (11) give us the maximum allowable channel utilization in the WiFi network for ZigBee node m (denoted as $\tilde{u}_{c,m}$) such that the ZigBee delay does not exceed D_{max}. Therefore, the maximum allowable WiFi channel utilization at coordinator c is given as

$$\tilde{u}_c = \min_{m \in A_c^{(z)}} \{\tilde{u}_{c,m}\}. \tag{12}$$

As shown in Algorithm 1, the coordinator monitors $u_c^{(w)}$ so as not to exceed $\tilde{u}_c$ according to the following procedure:

1) The related parameters are initialized as follows: $u_c^{(w)} = 0$ and $\tilde{u}_c$ is set by Eq. (12). We introduce two new parameters: a $BUSY$ flag to indicate whether the channel is busy and t_D to guarantee $D_{\max}$. We set $BUSY = false$ and t_D = 0.
2) Coordinator c monitors the channel to observe the current channel utilization and the received signal strength from each WiFi node. If $BUSY = false$, then
   - if $u_c^{(w)} > \tilde{u}_c$, the coordinator sets $BUSY = true$ and t_D = Current_time() $+ D_{max}$, and the total utilization to $sum = u_c^{(w)}$.
   - Otherwise, the coordinator increments the number of observations, N_c, and computes $sum = sum + u_c^{(w)}$. Then, if the average channel utilization sum/N_c is smaller than the maximum allowable utilization $\tilde{u}_c$, the coordinator sets $BUSY = false$.
3) If $BUSY = true$ and Current_time() $\geq t_D$, the coordinator sorts the MAC address list of the WiFi nodes in descending order of received signal strength observed at coordinator c, $P_{c,j}^{(w)}$. Then, the coordinator sends the list and $\tilde{u}_c$ to the AP.

Algorithm 2 Adaptive load control in an AP

Receive $\tilde{u}_c$ and the MAC address list from coordinator c
$u_a^{(w)} = 0$
for $\forall j \in A_c^{(w)}$ **do**
  $u_a^{(w)} = u_a^{(w)} + u_j^{(w)}$
end for
while $u_a^{(w)} > \tilde{u}_c$ **do**
  Search the next node j generating NRT traffic from the top of the MAC address list
  Send a control message to the identified node and remove it from the list
  $u_a^{(w)} = u_a^{(w)} - u_j^{(w)}$
end while

Upon receiving a message including $\tilde{u}_c$ and the MAC addresses from coordinator c, the AP performs the following procedure (Algorithm 2):

1) The AP sums the channel utilization of WiFi node $j \in A_c^{(w)}$, $u_j^{(w)}$ (denoted as $u_a^{(w)}$), the type of WiFi traffic being determined with the use of traffic classification.
2) If $u_a^{(w)} > \tilde{u}_c$, the AP conducts a search to identify the node generating NRT traffic from the top of the MAC address list. The AP then sends a control message to the identified node and removes it from the list, and the AP updates $u_a^{(w)}$ by subtracting the utilization of the throttled node. If, after the update, $u_a^{(w)} > \tilde{u}_c$, the AP finds the next node from the list and sends a control message to make it delay its transmissions. This process continues until $u_a^{(w)} \leq \tilde{u}_c$.
3) Every node that receives a control message from the AP starts a timer that expires after T_c seconds and delays NRT data transmission until the timer expires.

IV. Performance Evaluation

We evaluate the performance of our algorithm in ZigBee-based WBAN/WiFi coexistence environments in terms of the transmission delay of ZigBee packets from a ZigBee sensor to a coordinator.

A. Simulation Environment

We developed a discrete event-driven simulator to demonstrate the effectiveness of our adaptive load control algorithm in ZigBee-based WBAN/WiFi coexistence environments [9][11], and compared the transmission delay of the

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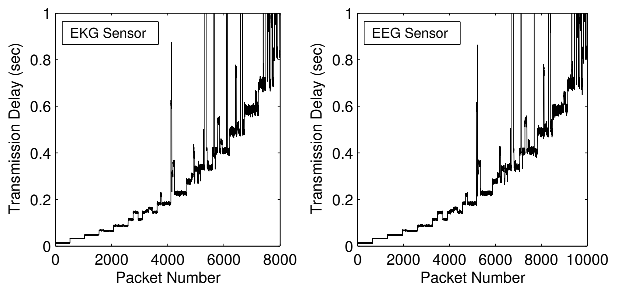
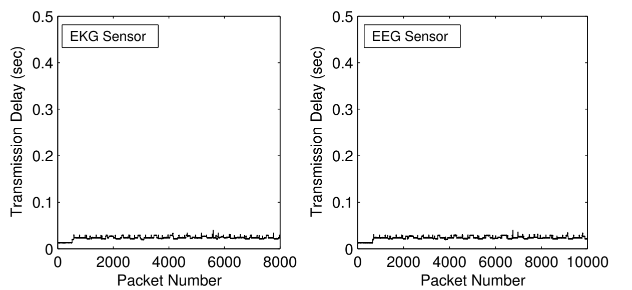
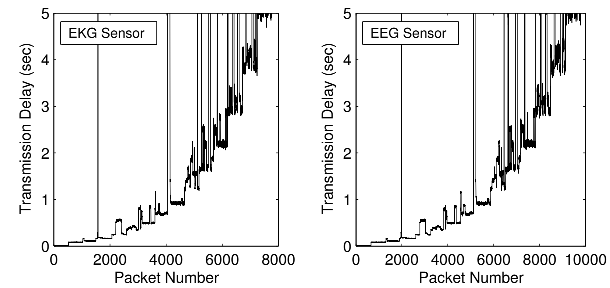


(a) Bridging

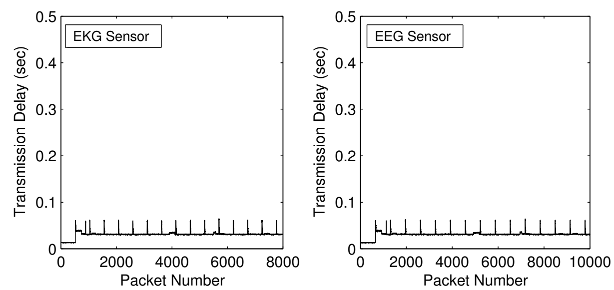


(b) Proposed

Fig. 2: Transmission delay of each ZigBee packet from EKG and EEG sensors in Case 1 when Traffic Model-I is used.



(a) Bridging



(b) Proposed

Fig. 3: Transmission delay of each ZigBee packet from EKG and EEG sensors in Case 2 when Traffic Model-I is used.

algorithm with that of a bridge-based scheme [9] referred to as ‘Bridging’, which assumes basically no WiFi interference.

The simulation area considered is a small apartment with “a living space of 62 square meters” [20]. In the simulation area, we place one AP in the center and two WiFi nodes (e.g., laptop or smartphone) at random distances (i.e., 1-10 m) from it. The WiFi network operates with a data rate of 11 Mbps. We use the Friss free space propagation model with a path-loss exponent of 2.

The ZigBee-based WBAN operates with a data rate of 250 Kbps. We place one ZigBee coordinator at a location 10 m away from the AP with ZigBee-based medical sensors (i.e., EKG and EEG) each located at distance of one meter from the coordinator [12][13]. The Carrier Sensing (CS) threshold for the WiFi network and the ZigBee-based WBAN are set to -70 dBm and -75 dBm, respectively. Table I summarizes the default values of the parameters used in the simulation [2][21][22].

We simulated two cases with two types of WiFi traffic generation models. In *Case 1*, one WiFi node generates RT traffic and another generates NRT traffic. In *Case 2*, all the WiFi nodes generate NRT traffic. The traffic models are as follows:

1) *Traffic Model-I*: WiFi traffic is artificially generated at the WiFi node. The traffic flow is characterized by its packet arrival pattern and payload statistics (i.e., mean packet length).
   - RT Traffic: “Following the behavior of standard pulse-code modulation codecs (e.g., G.711), voice sources generate one 80 bytes packet every 10 ms” [23].
   - NRT Traffic: NRT traffic arrives from the upper layer as a Poisson sequence, with exponentially distributed packet lengths [23]. The mean frame payload size is 1024 bytes, and the average rate is 20 Kbps.
2) *Traffic Model-II*: This model uses the testing sets. Application is randomly chosen among the applications selected in Section III according to the simulation case.

TABLE I: Parameter values for simulation

Parameter	Value	Parameter	Value
T_{bi}	30 ms	T_{sf}	30 ms
T_b	320 μs	L	48 bytes
T_{CCA}	640 μs	T_{SIFS}	10 μs
T_{ACK}	352 μs	$T_{ACK,TO}$	864 μs
P^{noise}	-90 dbm	T_c	500 ms
W_0	8	$W_X(X=2)$	32

We set the transmission rates of the EKG and EEG sensors to 64 and 80 kbps based on the sampling data, for which the sensors were sampled at 1000 Hz with 2 electrodes and at 500 Hz with 5 electrodes for EKG and EEG, respectively [24]-[26]. We estimate the transmission delay for a ZigBee packet only from a ZigBee sensor to a coordinator. In the simulation, we set the constraint for the maximum ZigBee delay D_{max} to 100 ms, since IEEE 802.15.6 specifies that an emergency alarm should be triggered in less than 1s [1].

Before applying our traffic classification to the AP, we performed an experiment to evaluate the overall accuracy, which is in terms of the ratio of the sum of all correctly classified frames to the sum of all frames in the testing sets. As inputs, we used the five serial frames [27]. We varied the size of dataset per application from 1,000 to 10,000 (in frames) in the experiment. We found that the accuracy increases until it reaches a maximum of 96.22 % at which the size of dataset is 5,000. In order to attain the maximum accuracy, we set the

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size of dataset to 5,000 in our traffic classification.

B. Simulation Results

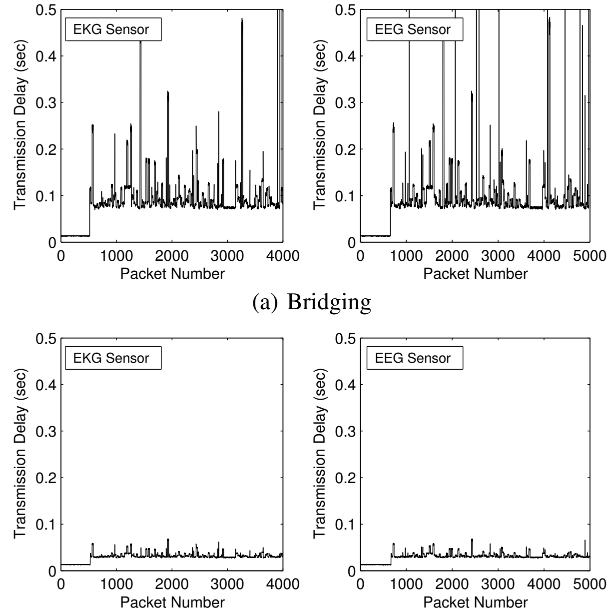
We demonstrate that the delay performance for the ZigBee-based WBAN is guaranteed by the proposed algorithm. Figure 2 plots the transmission delay experienced by ZigBee packets from each medical sensor to the coordinator in Case 1 when Traffic Model-I is used. It can be seen from Fig. 2 that the maximally tolerable delay requirement is guaranteed by the proposed algorithm for all packets sent from the two ZigBee-based medical sensors, in contrast to the Bridging approach, in which a delay of about 70 % packets exceeds D_{max} for both medical sensors. We can also observe from Fig. 3 that in Case 2, the proposed algorithm meets the delay requirement for the ZigBee-based WBAN, whereas delays of 89.3 % and 88.8 % packets exceed D_{max} in the Bridging approach.

Figure 4 plots the transmission delay experienced by a packet from each medical sensor to the coordinator in Case 1 when Traffic Model-II is used. It can be observed that the maximally tolerable delay requirement is guaranteed by the proposed algorithm, whereas in the Bridging approach, delays of about 48.1 % packets exceed D_{max} for both ZigBee sensors. We also can see from Fig. 5 that in Case 2, the proposed algorithm meets the delay requirement for the ZigBee-based WBAN, whereas delays of 24.1 % and 24.7 % packets exceed D_{max} in the Bridging approach.

When Traffic Model-I is used in the proposed algorithm, the highest ZigBee transmission delays are 39 ms and 64 ms for all the medical sensors in Cases 1 and 2, respectively. For Traffic Model-II, the highest ZigBee transmission delays are 67 ms and 68 ms for the EKG and EEG sensors of Case 1, respectively, and 78 ms and 77 ms for the EKG and EEG sensors of Case 2, respectively. Thus, we can see from Fig. 2-5 that the maximally tolerable delay requirement can be guaranteed by the proposed algorithm.

To see the effects of considering the patient's mobility on the performance of our algorithm and the Bridging approach, we compare the performance of the two approaches. In the simulation environment described above, we add one AP that has an overlapping area with the existing AP and employ the "Levy walk (LW) mobility model" to reflect "the patterns of human walks" [28]. In the LW model, "the patient's steps represent a flight followed by a pause." In the simulation, the flight lengths and pause times are truncated to [1, 50] m and [1, 100] s, respectively, following "the truncated Levy distribution" [28].

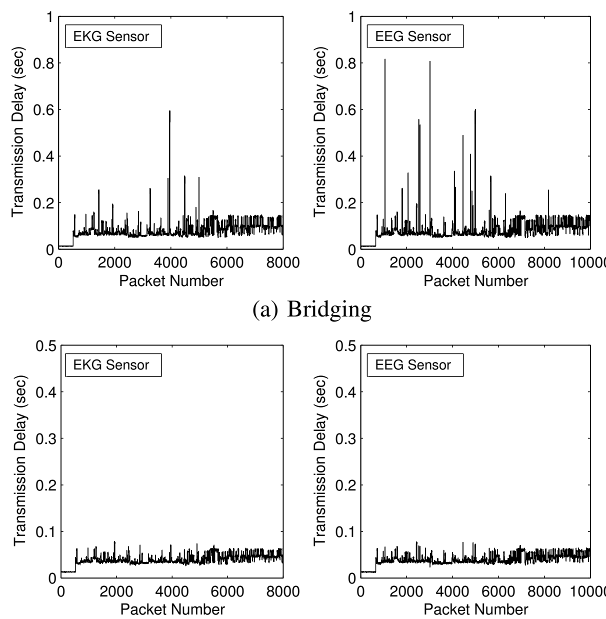
Figures 6 and 7 show the cumulative distribution function (CDF) of transmission delay for EKG and EEG sensors when Traffic Model-I and Traffic Model-II are used with the patient's mobility. We can see from Fig. 6 that the transmission delay of our algorithm for EKG sensors remains within an acceptable limit of less than 0.1 s for all cases, in contrast to the Bridging approach, which yields average delays of about 14.6 % and 26.2 % packets, exceeding D_{max} for Traffic Model-I and Traffic Model-II, respectively. We can see from Fig. 7 that the CDF of transmission delay for EEG sensors shows almost the same behavior as that of the EKG sensors for both cases when Traffic Model-I and Traffic Model-II are used. In the Bridging approach, average delays of about 14.73 % and 25.8 % packets exceed D_{max} for Traffic Model-I and Traffic Model-II, respectively. This is because the patient moves and the distance between the AP and the coordinator is varied. More specifically, the proposed algorithm provides reliable transmissions for the ZigBee-based WBAN even when the distance is small and the WiFi interference becomes high, in contrast to the Bridging approach, in which delays are



(a) Bridging

(b) Proposed

Fig. 4: Transmission delay for each ZigBee packet from EKG and EEG sensors in Case 1 when Traffic Model-II is used.



(a) Bridging

(b) Proposed

Fig. 5: Transmission delay for each ZigBee packet from EKG and EEG sensors in Case 2 when Traffic Model-II is used.

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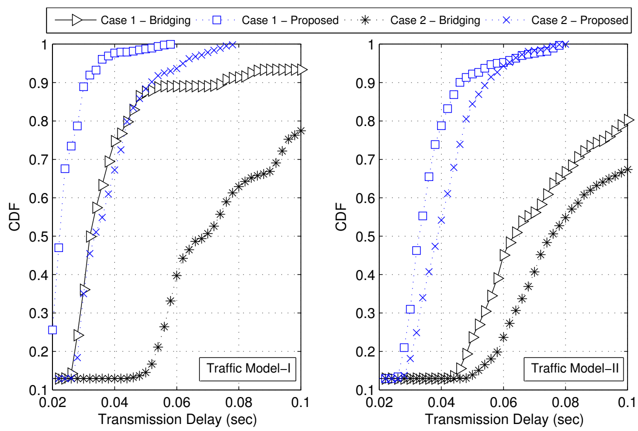

Fig. 6: CDF of transmission delay for EKG sensors when Traffic Model-I and Traffic Model-II are used with the patient's mobility.

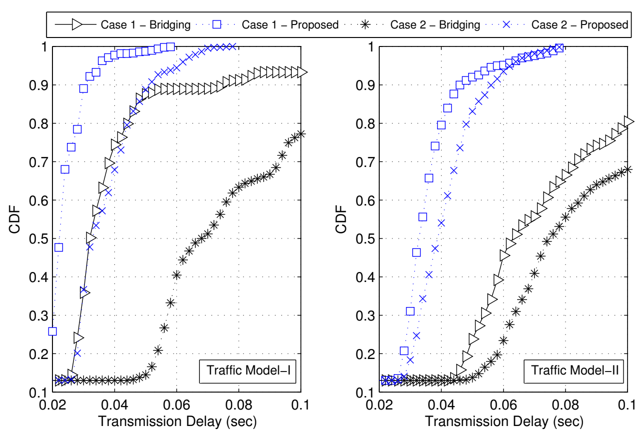

Fig. 7: CDF of transmission delay for EEG sensors when Traffic Model-I and Traffic Model-II are used with the patient's mobility.

affected by distance. Finally, we can see that, in comparison to legacy ZigBee-based WBAN/WiFi coexistence environments, the proposed algorithm guarantees the maximally tolerable delay requirement for ZigBee communications by performing adaptive load control in the WiFi network.

As shown in Fig. 8, to see the effects of our adaptive load control algorithm with NRT and RT traffic, we measure the transmission delay of BitTorrent and PPLive traffic in Case 1 when Traffic Model-II is used. It can be observed that the delay limits of 5 s for NRT applications and of 400 ms for RT applications [16] are guaranteed. It indicates that our algorithm does not disturb the reliable transmissions for both NRT and RT traffic.

V. Conclusion

In ZigBee-based WBANs with coexisting WiFi networks, most ZigBee channels overlap with IEEE 802.11 WiFi channels, resulting in increased delays for ZigBee packets due to interference. To solve this problem, we have proposed an adaptive load control algorithm that controls only the WiFi traffic generated from delay-tolerant applications dynamically

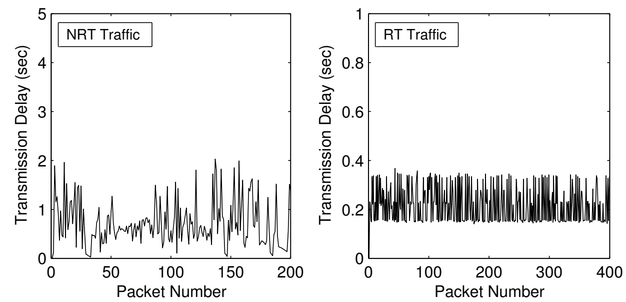

Fig. 8: Transmission delay of NRT and RT traffic in Case 1 when Traffic Model-II is used.

with the aim of guaranteeing that the delays experienced by ZigBee sensors do not exceed the maximally tolerable delay period. We have also analyzed the PER in ZigBee-based WBAN/WiFi coexistence networks and the delay from a ZigBee sensor to the coordinator while considering the effects of interference from the ZigBee network and other WiFi networks. In addition, the traffic classification is presented to classify applications. We have demonstrated via simulation results that the proposed algorithm guarantees the delay requirement for ZigBee sensors.

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