Robust License-free Body Area Network Access for Reliable Public m-Health Services

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***Abstract*—Public m-health service will enable care-givers to continuously monitor patients' vital signals wherever they are, using Body Area Networks (BANs). To make this service available to a large number of people everywhere, public m-health service should be implemented in a license-free frequency band. However, the coexistence problem inherent in such a medium that may be shared by many co-located systems may cause disruption of BAN transmissions. This paper addresses the above problem by proposing a Centralized BAN Access Scheme (CBAS) to improve service availability and robustness of BANs. CBAS puts most of the complexities in the gateway, which has less energy and resource constraints than the body nodes. The gateway monitors all the available channels and assigns an interference-free channel to each scheduled node. Extensive simulation results show the effectiveness of CBAS in reducing durations of service interruption and thus improving service reliability of a BAN.**

I. Introduction

Nowadays, increase of aging population and people with chronic diseases along with the demand for higher levels of life quality and well-being have raised a new challenge especially in developed countries. Public m-health is a promising service that meets this challenge by employing unobtrusive mobile technologies for ambulatory health monitoring. To enable public m-health service, patients may be equipped with Body Area Networks (BANs). A BAN generally consists of a gateway and a few body nodes which continuously sample vital signals of the human body and transmit them toward care centers via the gateway.

As medical data are crucially important, public m-health service has stringent reliability and robustness requirements. It means that streams of sampled data from BANs everywhere should be continuously delivered to the care center all the time. Fig. 1 illustrates configuration and topology of the stated public m-health system. This work focuses on developing a robust BAN access scheme to enable a reliable and feasible public m-health service for anywhere any-time patient monitoring. Before we present our solution, we shall consider which frequency band such a public m-health service should use.

If a specific channel in a dedicated frequency band is assigned to each BAN, reliable transmissions of medical data are guaranteed. The large bandwidth demand of this approach and the spectrum shortage problem make it not scalable to situations in which public m-health service is widely deployed. Also, to enable anywhere patient monitoring including in home and public locations, public m-health service cannot be implemented on the regulated Wireless Medical Telemetry Services (WMTS) band that is available in the USA, as "WMTS equipment may be used only within a health care facility," according to the Federal Communications Commission (FCC). Consequently, BANs in public m-health service should operate in license-free frequency bands to allow them to be widely deployed. The unlicensed Medical Implant Communication Service (MICS), Ultra Wideband (UWB) and Industrial Scientific Medical (ISM) bands are good candidates for this service. Since public m-health service generally targets continuous monitoring of vital signals such as temperature, heart and breathing rates which are transmitted from on-body sensor nodes in a BAN, MICS is also not suitable as this very narrow (3 MHz) frequency band is intended for transmission of radio signals within the human body [1].

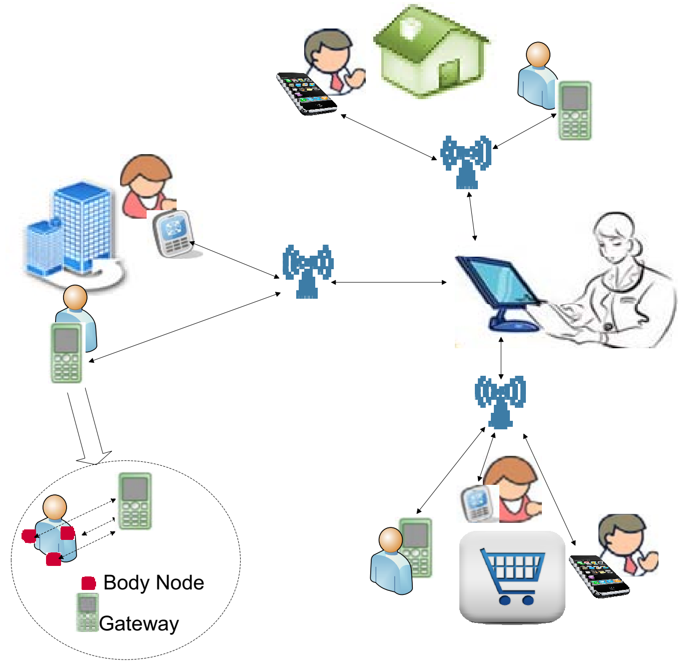

Fig. 1. Topology of a public m-health system employing BANs.

Providing reliable services through license-free bands is really challenging. A patient carrying a BAN may roam between different places such as home, office and public places. In each environment a variety of wireless systems may coexist in these license-free bands. So, the BAN carried by the patient experiences different levels of interference over time. Thus BANs for m-health monitoring need to deal with a dynamic interference environment comprised of multiple coexisting wireless systems. This challenge is further enlarged by the need to operate low-cost (and hence low complexity) body nodes with low data rate and low power consumption. Our previous investigation [2] shows that body nodes operating in the ISM band are easily victimized by much more powerful wireless local area network (WLAN) transmissions. Consequently, BANs operating in the ISM band are vulnerable to outages caused by interference, which presents a major challenge in providing continuous and robust public m-health service employing BANs.

To alleviate impacts of the above coexistence problem and enhance the ability of body nodes to reliably access the shared medium, a scheme that continuously finds available spaces in the shared spectrum and assigns them to body nodes is needed. This scheme should dynamically adapt to the different priority levels of packets generated by the body sensors, and be able to reliably recover from ongoing packet transmissions that are corrupted by interference.

The main contribution of this paper is the proposal of a Centralized BAN Access Scheme (CBAS) that enhances the availability of a BAN operating in a license-free band for continuous dissemination of physiological signals sensed around the patient's body over a public m-health system. Our approach puts most of the complexities in the gateway, which has less energy and resource constraints than the body nodes. The cognitive gateway senses for free spectrum in the license-free band and assigns the corresponding channels opportunistically to the body nodes for system access. We present simulation results to show that CBAS significantly increases service availability. While the performance evaluations focus on the ISM band, our proposed method is also directly applicable to BANs employing UWB access. To the best of our knowledge, this work is the first one to employ cognitive/opportunistic access in license-free bands to improve service robustness in the context of BANs.

II. Related Work

IEEE 802.15.4 is a standard predominantly used for low power and low rate wireless personal area networks (WPANs). The beacon-enabled mode of the IEEE 802.15.4 is recommended by the IEEE 802.15.6 Working Group for BANs [3]. The access protocol in IEEE 802.15.4 employs carrier sensed multiple access (CSMA) with 320μ sec back-off units (BUs) to regulate channel access after backoffs due to busy channel or collisions. There are two problems, resulting from specific features of 802.15.4, which make this standard unsuitable for BANs supporting a reliable public m-health service. These problems, as clarified in [2], are the beacon corruption problem and the noncompetitive time granularity problem. The former is resolved by the proposed recovery scheme in [2]. The latter arises from large BUs of the 802.15.4 protocol and causes WPAN to lose noticeable portion of channel availabilities in contention with co-located systems that have smaller BUs. So, a BAN employing IEEE 802.15.4 standard with such a large BU will have poor availability that makes it unsuitable for public m-health.

Several Time Division Multiple Access (TDMA) protocols have also been proposed to provide a reliable access for BANs. TDMA relies on tight synchronization between nodes to provide collision free access. However, in a multi-system coexistent environment, synchronization within a system does not prevent interference from non-cooperating co-located systems. So, even though a body node expects a free TDMA slot, its transmission may still collide with transmissions by other co-located systems. However, in the literature, all TDMA proposals assume that an interference-free medium is available to provide a reliable service for body nodes. In other words, service interruptions resulting from the coexistence problem have not yet been addressed in these proposals.

As an example, Marinkovic at el. in [4] proposed a TDMA scheme for BANs. Control information about assigned timeslots to each node is carried by some control messages. Therefore the performance of this scheme is heavily constrained by transmission reliability of these messages. This reliability is in question when BAN works in a shared environment. Furthermore, accommodation of emergency data (to support unexpected situations) is not addressed.

Authors in [5] follow the goal of reducing idle listening, collision and overhearing by proposing a TDMA structure. Both master and slaves periodically wake up after sleep time to initiate communications. Since channel condition (busy or idle) is not considered before transmissions, this scheme is effective only if the BAN is free from interference from coexisting systems. When external interference exists, this method is not capable of providing a reliable service.

Authors in [6] use channel information for adjusting transmission parameters to handle human body's fading effects. The adaptive modulation scheme adapts to variations of the channel but is not sufficient to deal with coexistence. For instance, in the presence of a persistent interference (like a running file transfer in a nearby WLAN) the BAN merely decreases its rate to adjust for the poor channel quality. This work does not provide any strategy to address throughput reduction in a BAN due to coexistence, which has a great impact on the service reliability and robustness of the BAN.

Authors in [7] introduce an interference-aware prioritized medium access scheme for e-health applications in a hospital environment. This scheme is implemented via two components: an inventory system that tracks the locations of co-located systems, and a Radio Access Controller (RAC) that uses this location information to compute an appropriate transmission power for each co-located system to mitigate interference. So, co-located systems should dynamically change their transmit power in cooperation with the RAC. In addition, to improve quality of service, the RAC centrally manages access of co-located systems to the shared channel. To accomplish this, wireless standards employed by all coexisting systems need to be modified such that their access requests are sent to the RAC using the proposed request-to-send/clear-to-send (RTS/CTS) procedure. Such modifications may not be practical for all wireless standards employed by participating systems. Also, some wireless transceivers are not capable of changing their transmit power dynamically. Since this method requires that each service area be equipped with the two new components, the method may not be suitable for public m-health service that requires global or wide-area coverage.

A cognitive radio approach for telemedicine services employing secondary access to spectrum holes left vacant by primary users is considered in [8]. This is a beaconing scheme in which nodes periodically wake up at the start of each sensing period and keep channel listening until they receive a beacon, which informs them about their transmission schedules. Emergency traffic is transmitted between the start of the sensing period and beacon transmission. Such a network, as a secondary user of spectrum licensed to the primary user, should confines its impact on primary user's traffic to a specific disruption limit which is defined by the channel owner. However, nodes transmit according to the schedule they have received in the most recent beacon regardless of the primary user's activity. Furthermore, whereas secondary access to licensed primary spectrum is widely considered as an effective approach to alleviate the shortage of wireless spectrum for broadband Internet access, the use of this approach in BANs for public m-health may not be appropriate due to potential service disruptions when the primary user becomes active, as well as interference from other coexisting secondary systems. However, the principle of cognitive identification of free channels for opportunistic access that avoids interference from coexisting systems can be applied to shared access in license-free bands, as we are proposing in this paper.

Our survey shows that there is a lack of good solution for providing reliable wireless access over license-free spectrum in BANs for public m-health services. This paper fills the void by proposing a robust access scheme, CBAS, for license-free BANs operating in the presence of coexisting systems.

III. System Requirements

An important element of public m-health service is the ability to provide continuous monitoring of human physiological conditions or signals such as temperature, heart and breathing rates. This can be accomplished by a BAN in which the body nodes monitor these signals with specific sampling frequencies and report these periodic data to a healthcare center through the gateway. Sampling rates vary depending on the body signal. When the sampled data for some body signal are not within the acceptable range, an emergency situation may be declared. These emergency data need to be received by the healthcare center with minimal delays before the patient's condition gets worse. In addition, on-demand data may be generated in treatments (e.g., drug delivery) or surgical operations in which a specific body node is called upon by the gateway to sample and report its measurement. Thus body nodes should always be ready to work on demand and report its recent measurements to the gateway.

These on-body BANs typically include a few body nodes and a powerful gateway. The limited size of the network relaxes scalability concern and makes centralized schemes practical for BANs. Therefore, the gateway may work as a central node and employ a higher transmit power so that its transmissions are received by all body nodes. This architecture has a star topology. In a network with star topology, transmissions take place only between the master and the slaves and no direct slave-to-slave link is established. In this case the gateway functions as the master, which may communicate with body node over channel x over one instance and channel y at another one. Therefore there is no requirement for the whole network to be tuned on a single frequency if the gateway communicates with one node at a time.

As we have discussed, BANs enabling public m-health must provide an anywhere anytime service to monitor patients' body signals. A license-free frequency band is therefore most suitable for such a service. The ISM and UWB bands are both appropriate frequency bands for BANs. Both provide a pool of orthogonal channels for BAN operations. For example, if a BAN is implemented based on the physical layer of the IEEE 802.15.4 standard, 16 non-overlapping channels in the ISM band would potentially be available for its operation. Nevertheless, because of the coexistence of other wireless systems in these license-free bands, to achieve the robustness required to support public m-health, BANs need to employ access schemes capable of dealing with patterns of interference that dynamically change over time. Such access schemes need to operate under the constraint that body nodes have lower transmit power and less processing capability than the gateway.

The CBAS scheme presented in the next section is designed to satisfy the above requirements.

IV. Centralized BAN Access Scheme

A. Assumptions

The proposed CBAS has been designed to operate under the following assumptions regarding the physical layer capability and transmission environment:

- *Control Channel*: A dedicated control channel is available for exchanging of control information, e.g., channel assignment broadcasts and access requests, between the gateway and body nodes. In the 3-10 GHz UWB band, the control channel can be realized using a long spreading code to minimize interference from and to other coexisting systems [9]. In the 2.4 GHz ISM band, where interference from high power WLAN transmissions is dominant, the control channel can be implemented using the part of the spectrum that is not occupied by WLANs. For instance, channels 13 and 14 of IEEE 802.11 WLANs operating in the 2.4 GHz ISM band are not used by most WLAN devices in N. America [10] due to transmit power restrictions, and they may therefore be used for the CBAS control channel. Although this choice protects the control channel from high powered 802.11 WLAN interference, systems like IEEE 802.15.1 or IEEE 802.15.4 WPANs may still interfere with the control channel. However, WPANs generally have much lower transmit power, so that interference from these systems is less of a concern. Thus in all cases, realization of a dedicated control channel that allows the gateway to send control messages to the body nodes with a high reliability is feasible.

- Each body node has a unique identity (ID), and the gateway has complete information about this ID and body nodes' sampling rates. A small ID space is needed since a BAN includes only a relatively small numbers of nodes.
- For power conservation, body nodes enter the low-power sleep mode when they are not exchanging data with the gateway. Body nodes are equipped with passive radio frequency (RF) modules [11] that allow them to receive commands from the gateway on the control channel when they are asleep. A command addressing a body node using its unique ID causes the node to wake up and process the command.
- A pool of *h* orthogonal channels is available for BAN operation; e.g., there are 16 candidate channels for 802.15.4 WPANs in the license-free 2.4 GHz ISM band.
- The gateway has the ability to sense the state of all the channels in the channel pool at the same time; in essence, it has cognitive radio capability. As in other work [12], channel sensing is assumed to be perfect.
- The states of channels sensed by the gateway are consistent with that seen by body nodes; i.e., if channel x is perceived as idle by the gateway it can be reliably used for communications between the gateway and any body node. This assumption is also used in [12] for a Bluetooth system, and is reasonable in our case since body nodes are less than 2 meters from the gateway and the whole BAN can be considered one entity from an external viewpoint.
- In addition to supporting the WPAN protocol used by the BAN, the gateway can also transmit at high power using the IEEE 802.11 protocol.

B. *Description of Centralized BAN Access Scheme*

Since body nodes have low transmit power, they usually are not able to force high power interferers to respect BAN traffic requirements. In other words, in the presence of contenders with high transmit power, BAN usually does not succeed in contending for access to the shared license-free band. So, access of body nodes is generally restricted to unused spaces of the spectrum. Since traffic of co-located wireless systems does not have a predictable pattern, these unused spaces are scattered over time. So, in spite of the requirement of public m-health for a reliable and robust service, access of body nodes to the shared medium faces unpredictable interruptions, which varies across the pool of orthogonal channels due to different interference levels. CBAS exploits this diversity to improve service reliability of a BAN.

To illustrate, suppose there is a pool of three orthogonal channels for BAN's operation and co-located systems occupy these channels as shown in Fig. 2. Suppose that the target BAN is tuned to CH1. Consequently, its access to the shared medium is excluded in the dashed parts of Fig. 2(a), which indicates that BAN service is intermittently interrupted. However, if at the time of service interruption on CH1, the BAN is tuned to another available channel (if exists), these interruptions are reduced and service reliability improves.

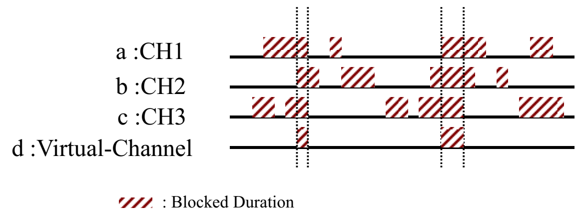

Fig. 2. Channel Availability Pattern

In this example, by sensing channel availability over CH2 and CH3, availability of BAN access to the shared medium is expanded to that of the Virtual-Channel shown in Fig. 2(d). The Virtual-Channel represents the capacity of the shared medium extracted for BAN access when CBAS opportunistically captures the available durations of all candidate channels. In Fig. 2(d), un-shaded spaces of the Virtual-Channel represent the total access availability for the BAN. Clearly, this improvement in service reliability of BAN traces back to the availability of a channel pool. In other words, if the BAN is constrained to work on only a specific channel all the time, like an 802.15.4-based BAN, its chance of accessing the channel is notably reduced by the activities of coexistent systems. However, channel access is potentially enhanced if the BAN dynamically tunes to available channels.

Based on the above discussion, our proposed CBAS operates as follows, which is summarized in Table I:

Step 1: The gateway continuously senses all channels that exist in the pool of orthogonal candidate channels to detect those that are unoccupied, as well as idle spaces that occur between transmissions of co-located networks in the occupied channels, and assigns them to body nodes. It is possible that more than one channels are perceived as idle by the gateway. If so, one of the available channels is chosen based on the specific channel selection strategy that the gateway follows. For example, the gateway chooses an unoccupied channel and stays on it until it becomes unavailable or degraded.

Step 2: The gateway exploits the spectrum space to improve BAN access by allocating the best available channel to the next body node scheduled for transmission, based on the gateway's knowledge of the body nodes' sampling rates. The gateway sends an RTS (using 802.11 protocol) on the allocated channel with an appropriate reservation time to capture it for the duration of the expected data exchange, and sends a command (including the ID of target node plus information about the chosen frequency channel) on the control channel to the specific body node.

Step 3: The passive RF module of the target body node, which finds its ID matches that in the command sent by the gateway on the control channel, wakes up the body node to process the command.

Step 4: The body node switches to the assigned channel and exchange data with the gateway on that channel. When data transmission is finished, the body node tunes its radio to the control channel and goes back to sleep.

TABLE I
CENTRALIZED BAN ACCESS SCHEME (CBAS)

1) Gateway continuously monitors availability of channels in the BAN's channel pool and update the list of available channels.
2) While (list of available channels is not empty) {
   a) Gateway selects one of the channels from the list, e.g. CH_x.
   b) Gateway selects one of the body nodes, as a target node,based on its specific scheduling algorithm.
   c) Gateway sets transmission duration, Δ_{TX}, in an RTS message and sends it with high power through CH_x.
   d) Gateway sends a command of triple <*ID* of the target node,CH_x, Δ_{TX}> on the control channel.
   e) All body nodes except the target node ignore the command.
   f) The target body node tunes to CH_x and starts its transmission for Δ_{TX} seconds.
   g) After Δ_{TX} seconds, the target node tunes its transceiver to the control channel. }
3) Go to step 2

C. Characteristics and Features of CBAS

In this section, specific characteristics of CBAS in addressing requirements of BANs are discussed.

1) *CBAS properly services all three categories of periodic, on-demand and emergency data.*
For serving periodic data, the free channels identified by the gateway are allocated to body nodes based on the knowledge that the gateway has about the nodes' sampling rates. Since requests for on-demand traffic are initiated by the gateway, this kind of data is served like periodic data. In fact, when the gateway requires body signal measurements from a specific body node, it simply assigns a free channel. Finally, for handling emergency situations, when node infers an unusual event, it immediately sends a request through the control channel. Once the gateway receives this request and finds one of candidate channels free, the gateway assigns the free channel to the requesting node. If the measured data is transmitted with the least delay, medical staff can handle it right away before the patient's condition gets worse.

2) *CBAS addresses energy conservatism requirement of BANs.*
Since sensing for free channels, assigning them to body nodes, and initiating a link are done centrally at the gateway, CBAS frees the body nodes from the complexities and energy consuming procedures by concentrating these at the gateway. Furthermore, by incorporating passive RF modules [11] in the body nodes, they can switch to low-energy sleep mode as soon as possible without wasting their precious energy on idle listening. Passive RF modules bring the benefit of energy harvesting and no quiescent power consumption from the battery when a body node is waiting for the next command. In other words, although a body node has no knowledge about when the gateway assigns an available channel to it, it does not need to spend energy listening to the control channel all the time. When a command arrives in the control channel, the passive RF module recovers energy from the command to decode the command and wakes up the body node to further process the command if its ID matches that of the node. So, These features make this proposal appropriate for providing energy efficient BAN service and reduce unavailability due to battery drain.

3) *CBAS protects low power transmissions of body nodes from being perceived as noise by co-located systems.*
IEEE 802.11 and its compliant networks are CSMA-based wireless systems that employ Clear Channel Assessment (CCA) scheme to check the availability of the medium before capturing it. CCA is a conservative approach to reduce collision between systems which have access to a shared medium. As it is likely that a BAN works in a shared medium with co-located CSMA-based systems, these systems are expected to defer their contention for the shared medium when the BAN is active. This expectation is mostly satisfied by coexisting low power WPANs, such as those employing the IEEE 802.15.4 standard, as their transmit power levels are similar to that of the BAN. So CCA works in a reciprocal manner, and ongoing BAN transmissions are less likely to be interfered by low power WPANs. However, uneven channel perception problem occurs between the BAN and coexisting networks employing higher transmit power levels [13]. The big difference in the BAN and coexisting network's transmit power levels means that the coexisting network's CCA may sense a clear channel but the BAN's CCA senses a busy channel. This problem penalizes the BAN and makes energy based CCAs insufficient for detecting channel occupancy and avoiding collision. Specifically, high transmit power levels plus high CCA thresholds of IEEE 802.11 WLANs seriously threaten low power BAN transmissions, which may be ignored by WLANs as noise. Consequently, protection of BAN packets from potential 802.11 signals is necessary. To accomplish this, we exploit the possibility of implementing the gateway in contemporary portable computing devices supporting multiple radio interfaces, such as smart phones. When the gateway decides on allocation of a specific available channel to a body node, it sends an RTS with high power on that channel according to the 802.11 standard [14] before sending a command via the control channel (see line 2.c in Table I). The RTS includes the expected duration of the data exchange between the gateway and the body, which is specified as Δ_{TX} in Table I. All

802.11 stations receiving the RTS set their Network Allocation Vector (NAV) with the announced duration. Consequently, the BAN is free from IEEE 802.11 interference because all coexisting 802.11 systems defer their channel access for the NAV duration.

V. PERFORMANCE EVALUATIONS

In this section, the effect of CBAS schemes on BAN's service reliability is evaluated via computer simulations using the OPNET simulator. We consider BAN operation in the 2.4 GHz ISM band using physical layer parameters and frame structure specified for IEEE 802.15.4 WPANs [15], but modify the channel access to follow our CBAS proposal. The open source toolkit [16] is used for implementation of IEEE 802.15.4 beacon-enabled mode. We consider a BAN, consisting of a gateway and three body nodes, which is tuned to CH1. Also, there are two co-located WLAN work-stations on CH1. Packet arrivals at the WLAN stations are poisson with parameters λ_1 and λ_2. An analyzer is employed to derive statistics about the percentage of time,σ, in which channel is occupied by WLAN transmissions. By changing λ_1 and λ_2, the analyzer derives different values of σ as a representation of the level of interference the BAN experiences from coexistent WLAN systems. Due to the uneven channel perception problem, the effect of WPAN interference on a co-located WLAN is to increase packet error rate of WLAN transmissions. Simply put, the impact of WPAN does not change WLAN's data rate [12]. WLAN and BAN packets are 1400 and 256 Bytes, transmitted at channel data rates of 11Mbps and 250Kbps, respectively.

Since we want to explore service reliability of a BAN, we set very high arrival rates for body nodes to ensure that the BAN aggressively tries to access the shared medium. With this setting, the BAN always has packets for transmissions or equivalently the queues of body nodes are never empty and the BAN persistently tries to capture the medium. In this situation, the time duration between two consecutive BAN transmissions, W_i in Fig. 3, shows how long the BAN should wait until it could transmit again. Conversely, it indicates how long the channel is continuously available for BAN operation. So, smaller ($\overline{W_i}$) specifies more service availabilities for nodes.

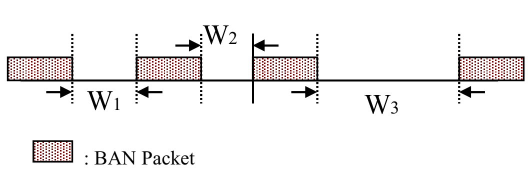

Fig. 3. Waiting Duration Between Two Consecutive BAN Packets

Fig. 4 shows the average waiting durations, i.e. $\overline{W_i}$, of CBAS with pools of two and three channels in comparison with a BAN following the IEEE 802.15.4 standard operating over a single channel, and a single channel 802.15.4-based BAN enhanced with the recovery scheme proposed in [2].

We also enhanced 802.15.4 with the proposed recovery scheme in [2] to compare how much service reliability of 802.15.4 is improved by employment of this scheme. As Fig. 4 shows, when 802.15.4 is enhanced with this recovery scheme, waiting duration is reduced because beacon corruption is addressed properly.

Now, to evaluate the effect of CBAS, we add CH2 and CH3 with the same parameters as CH1 and run two scenarios with channel pool of CH1, CH2 and CH1, CH2, CH3. In these scenarios, there are two WLAN stations per channel with exponential arrivals with parameters of λ_1 and λ_2. So, all three channels experience the same average level of WLAN interference but at random time intervals.

As the selection strategy in this part of simulation, when gateway finds more than one channel available, it selects the channel that it has recently used. However, if the recently used channel is not between available channels, gateway chooses one of the available channels randomly.

In CBAS, the gateway centrally manages access of body nodes to the available channels of the channel pool. For large WLAN traffic intensities (high values of σ) as Fig. 4 shows, $\overline{W_i}$ for CBAS is noticeably smaller than that of 802.15.4 and 802.15.4+recovery scheme. Reasons of this reduction are:

- Gateway captures all the unused spaces of {CH1, CH2}/ {CH1, CH2, CH3} to improve service availability of the body nodes.
- Body nodes do not participate in CSMA procedure to access the medium. So, they do not lose their access opportunities because of their large BU.
- 802.15.4 protocol overheads are removed because body nodes are not required to postpone their medium access to synch with the coordinator by receiving beacon and to sense two consecutive idle CCAs before their transmissions.

Fig. 5 shows the effective service rate (throughput) of the BAN for each scheme. This figure confirms the above discussion in a different direction. Note that throughput is

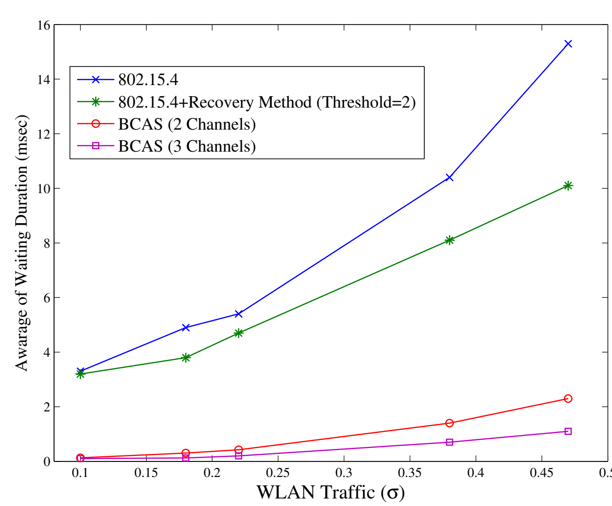

Fig. 4. Average of Waiting Duration ($\overline{W_i}$)

calculated as:

$$Throughput = \frac{\bar{N} \times 256 \times 8}{250000} bps$$

where $\bar{N}$ is the average number of body nodes' packets received successfully by the gateway.

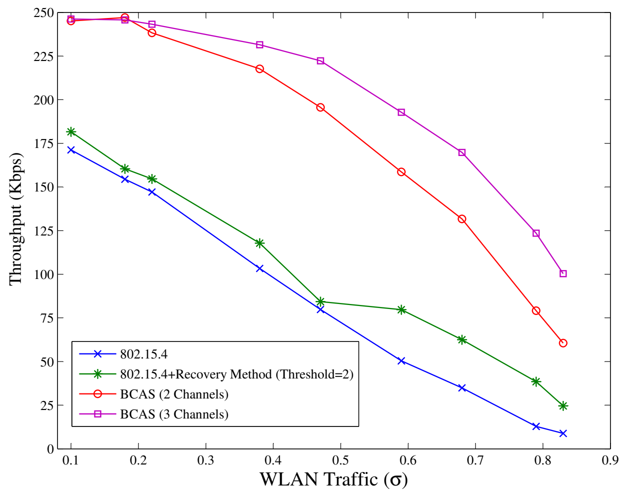

Fig. 5. Effective Service Rate of BAN

Since the queues of body nodes may not be full all the time, we need a more precise insight about service reliability of a BAN. For this reason, the analyzer extracts statistics about average of idle and busy durations represented by $\overline{X_{idle}}$ and $\overline{X_{busy}}$, respectively. Analyzer perceives the channel as busy when WLAN is in transmission. As soon as transmission of WLAN packet is finished, analyzer finds channel as idle. So, we want to know how frequently the channel becomes busy and consequently service of BAN faces interruption.

The proposed CBAS ensures that the BAN has access to the medium as long as one of candidate channels in the channel pool is found idle by the gateway and it loses access when all candidate channels become busy. It means that BAN transits frequently between two states which we call them busy and idle states in the rest.

During busy state, BAN operation is stalled and its service is interrupted since there is no available channel to be captured. Once at least one of candidate channels becomes idle, BAN transits to idle state and its service is resumed. As soon as all channels become busy, the BAN leaves idle state and transits to busy state. So, we can assume that time is divided into cycles and each cycle includes a consecutive idle and busy periods. Therefore, when gateway manages body nodes based on CBAS, service of BAN is limited to $\overline{X_{idle}}$ durations which are scattered across time. In fact, for WLAN traffic intensity of σ, after $\overline{X_{idle}}$ seconds, service of BAN deals with interruption for $\overline{X_{busy}}$ and this pattern is repeated.

The goal of CBAS is reduction of $\overline{X_{busy}}$ to provide a more robust service for body nodes. This approach exploits availabilities of all candidate channels to provide larger $\overline{X_{idle}}$ and smaller $\overline{X_{busy}}$, which means less channel interruption for service of body nodes. Figures 6, 7 and 8 illustrate variations of $\overline{X_{idle}}$ and $\overline{X_{busy}}$ when WLAN traffic intensity, σ, changes.

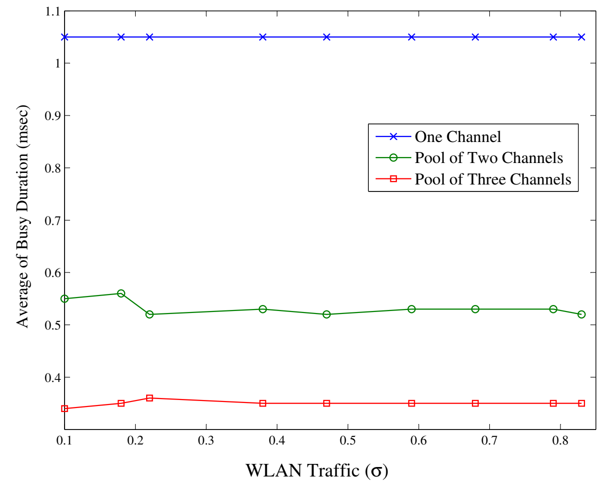

Fig. 6. Average of Busy Periods, i.e. $\overline{X_{busy}}$

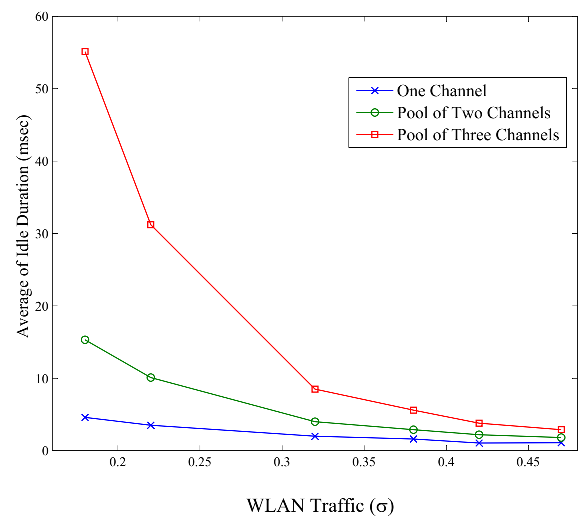

Fig. 7. Average of Idle Periods, $\overline{X_{idle}}$, when σ<45%

Since transmission of one WLAN packet lasts 1 ms, as Fig. 6 illustrates, $\overline{X_{busy}}\sim$1ms for the case of one channel. Also, $\overline{X_{idle}}$ represents average of idle durations happen between WLAN transmissions. As we expect, when a channel pool of {CH1,CH2} is available, $\overline{X_{busy}}$ represents durations in which both of CH1 and CH2 are busy and consequently the gateway could not find an available channel for BAN operation. So, service of BAN faces interruption. Similarly, $\overline{X_{idle}}$ represents average of durations in which at least one of the channels in the channel pool is available. For example, when each channel experiences $\sigma\sim$50%, the BAN with only one channel deals with interruption of $\sim$1 ms after service duration of 1.1 ms, see Figures 6 and 8. But, when the BAN employs CBAS with a pool of {CH1, CH2}, BAN service deals with interruptions of 0.53 ms after each 1.8 ms. Access availability is further

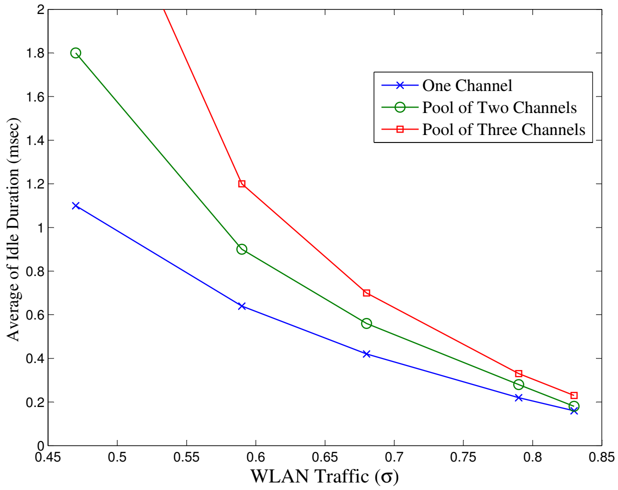

Fig. 8. Average of Idle Periods, $\overline{X_{idle}}$, when 45%<σ

improved when CBAS has access to the pool {CH1, CH2, CH3}. In this case $\overline{X_{idle}}$ is increased to 2.9 ms and $\overline{X_{busy}}$ gets reduced to 0.35 ms.

VI. CONCLUSION

Public m-health for continuous monitoring of patients' vital signs anytime and anywhere is practical only when a reliable BAN is available for sensing the body signals and conveying them to the healthcare center via a gateway. License-free bands are suitable for BANs as they are available everywhere, but faces the challenge of link disruptions due to interference from coexisting systems. We have addressed this challenge by proposing CBAS, a centralized access scheme that employs cognitive spectrum sensing capability at the gateway for opportunistic access to free channels. We have presented simulation results, which confirm that a 802.15.4-based BAN suffers from highly unreliable service when it is subject to frequent interruptions from co-located WLAN stations. In contrast, results show that the proposed CBAS significantly improves the BAN's channel availability without imposing processing overheads on low complexity body nodes. By employing the proposed CBAS to improve the reliability and robustness of BANs, realization of public m-health will take one big step forward. For the future work, we intend to modify CBAS to support multi-hop transmissions from body nodes toward gateway. This modification addresses time variant channel condition problem that may endanger direct single-hop packet reception via gateway.

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