MAC PROTOCOL IN WIRELESS BODY AREA NETWORKS FOR E-HEALTH: CHALLENGES AND A CONTEXT-AWARE DESIGN

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ABSTRACT

Wireless Body Area Networks (WBAN) is a promising low power technology that enables the communications between body area sensor nodes and a central coordinator. It targets at many applications in e-Health services. In WBAN, different data sources generate time-varying traffic. Large traffic volume may result in intolerant latency and thus it is extremely important that the most significant data can always be delivered in a real-time fashion. Besides, data transmission may suffer from deep fading and packets loss due to the dynamic on-body channel induced by movements and surrounding environment. Hence, energy-efficient medium access control (MAC) is crucially needed to allocate transmission bandwidth and to ensure reliable transmission considering WBAN contexts, i.e., time-varying human and environment conditions. To improve both efficiency and reliability, we investigate the challenges in the development of WBAN MAC design. Furthermore, based on the traffic nature and channel status, we introduce a context-aware MAC protocol to meet time-varying requirements of WBAN. We have demonstrated that the proposed protocol is able to reduce latency, energy consumption, and packet loss rate, as well as to achieve a reasonable trade-off between efficiency and reliability.

INTRODUCTION

With the development of miniaturized, high-performance, and low-power sensor nodes, and the recent advances in wireless networking technologies, communications in or around human body using wireless body area networks (WBAN) have become practically feasible. Healthcare community and engineering industry have shown increased interests in WBAN, since this emerging system provides efficiency to e-Health applications, e.g., remote patient monitoring and medical care. The general architecture of a WBAN-based system is illustrated in Fig. 1. WBAN is body-centric and it comprises two categories of nodes: in-body, on-body or around-body sensor nodes, and coordinator equipped on human body. These nodes, covering a short range (usually 2–3 m), usually form a star-topology network, where the coordinator and sensor nodes exchange data directly in one-hop communication. Thus different types of information regarding human body can be collected and then transmitted to the coordinator for analysis and display. Through wireless and broadband network, the coordinator can also forward data to remote servers. Thus body area information, such as body vital signs, human motions, and surrounding environment status, can be collected without interrupting people's normal activities.

The most important issue we should consider in WBAN is energy efficiency since sensor nodes only have batteries with limited capacity and it is inconvenient to recharge or replace the batteries, especially for implanted sensors. Besides, various kinds of sensor nodes, such as blood pressure, heart rate, electrocardiogram (ECG), electroencephalogram (EEG), have very different demands in terms of data rate and latency. These demands are usually dynamic and dictated by the time-varying conditions of human body and environment. For example, when a cardiomyopathy patient is doing exercise, time-critical signals, such as heart rate and ECG, need to be delivered in a real-time fashion rather than the usual periodic transmission. Furthermore, the robustness of WBAN should be guaranteed against the channel fading in WBAN caused by energy absorption, body movement, and multipath due to surrounding environment [1]. For example, when one walks and moves his/her arms or legs between some transmitter and receiver antenna, transmitted packets may suffer deep fading and packets loss. In order to combat the aforementioned adversaries of WBAN, proper channel access and resource allocation mechanism is critically needed to control the communications and duty cycle of nodes. Therefore, designing an appropriate medium access control (MAC) protocol for WBAN becomes

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imperative in order to provide both efficiency and reliability.

According to the special design requirements for WBAN, the MAC protocol should have the ability to dynamically change the transmission strategies for the nodes when WBAN context, i.e., people's activity or environmental condition, varies, as well as to proactively minimize the power consumption to prolong the lifetime of nodes. In this article, we focus on how the idea of context awareness can be exploited to improve WBAN in terms of efficiency and reliability. We also present main thrust of the design for such a context-aware MAC protocol.

The rest of the article is organized as follows. We first present a review of existing MAC protocols for wireless sensor networks (WSN), and explain why such designs cannot be directly adopted for WBAN. We then address various challenges on MAC protocol design for WBAN based on existing works. Next, we introduce a context-aware MAC protocol, including the hybrid MAC superframe structure and the design for traffic-aware and channel-aware functions, to meet the requirements of WBAN. Finally, we conclude this article with a summary and discuss the future work regarding enhancing WBAN MAC design.

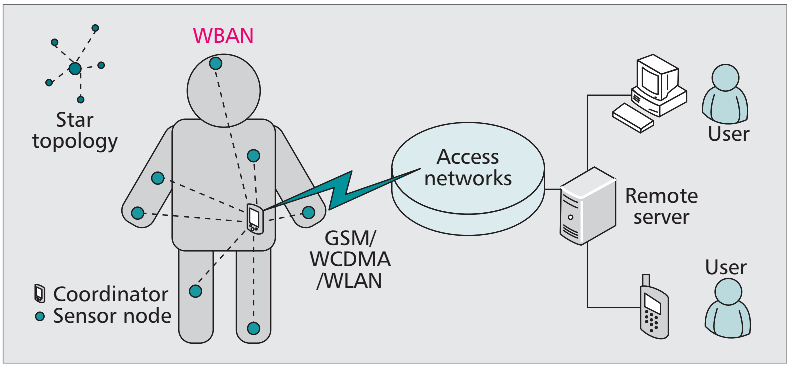

Figure 1. *General architecture of a WBAN-based system.*

A Review of MAC Protocols in Wireless Networks

MAC protocols for WSN have been widely explored. They can be categorized into two types: contention-based and schedule-based. In contention-based protocols, such as Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), sensors have to compete for the channel for transmission opportunity. Such protocols have no need to establish infrastructure and have shown good scalability. However, contention among nodes may incur packet collisions. Schedule-based protocols, such as Time Division Multiple Access (TDMA), divide the channel into time slots and explicitly assign slots to nodes. Each node transmits data in their own slots and keeps asleep in other slots. Consequently, collisions are avoided and energy wastage is reduced. However, the performance of TDMA-based designs is deteriorated due to the large overhead necessitated by the synchronization.

The primary concern of conventional WSN is power conservation rather than quality of service (QoS), such as data rate, latency and reliability, which, however, are essential in WBAN [10]. A WSN is also relatively stationary, whereas the WBAN worn by moving people is highly mobile. Besides, MAC protocols for WSN usually target at a large number of nodes with multi-hop communication, which makes them distributed in nature. However, this is not required in WBAN [10]. Hence, WSN MAC protocols cannot be directly used in WBAN.

IEEE established the 802.15.6 task group to standardize the MAC layer of WBAN in November 2007. The recently published standard draft [11] provides flexibility to protocol designers by recommending the use of several MAC layer techniques. However, how to combine some or all of these recommended techniques to form a particular WBAN MAC design is not specified. Many recently developed WBAN implementations use IEEE 802.15.4 [3], which is currently the principle low power low rate mechanism for short-range communications. In the beacon-enabled mode of 802.15.4 MAC, the superframe has an active part, including beacon, contention access period (CAP) and contention free period (CFP), and an inactive part where nodes stay in sleep state. In beacon period, beacon packets are periodically broadcasted by the coordinator for synchronization and superframe definition. Nodes compete for transmission opportunity in CAP using slotted CSMA/CA mechanism. Meanwhile, nodes may also request up to seven guarantee time slots (GTSs) in CFP for time-critical applications. In non-beacon-enabled mode, unslotted CSMA/CA is used for all transmissions but the ACK. Despite of its widespread usage, 802.15.4 is not the best solution for WBAN because it cannot support high data rate applications (>250kb/s) and it targets at relatively long transmission distance (10–75m) [3].

Recently, there are several MAC protocols that have been designed for WBAN [4–8]. A TDMA-based MAC protocol to reduce collision and energy cost is proposed in [4]. Initially, each slave node is assigned one slot by the master node. When a slave node sends an alarm, it can obtain one extra slot for transmission. In [5], an energy efficient MAC protocol using modified TDMA structure with extra reserved slots is proposed. The reserved slots are used for retransmission according to sensors' requests. A power efficient MAC protocol with TDMA-based superframe structure is proposed to support normal, on-demand and emergency traffic in [6]. Two different wakeup strategies are used for efficient communications. Another TDMA-based MAC protocol, H-MAC [7], utilizes a novel synchronization scheme. Heartbeat rhythm information extracted from the sensory data is exploited to synchronize the sensors. Thus periodic exchange of synchronization information is avoided and power consumption is reduced. In [8], a contention-based BAN designed for falls assessment is presented to guarantee the latency requirement of different data. High priority nodes can interrupt low priority nodes and exploit data fusion to improve throughput. Although the work in [8] meets partial requirements for WBAN, a comprehensive consideration of WBAN's specific features is necessary to meet the stringent requirements of WBAN. A wide range of challenging issues need to be resolved for WBAN MAC design and will be presented in the next.

Design Challenges for WBAN MAC Protocol

The design challenges, including energy efficiency, heterogeneous and dynamic traffic, and fading channel, and comparisons of existing works based on such challenges shall be discussed in detail in this section. The following discussions focus on healthcare monitoring, but they are applicable to other e-health applications.

Energy Efficiency

One of the most critical challenges for WBAN MAC protocol is energy efficiency. Despite the limited battery power of body sensors, some devices are required to work unobtrusively for months or even years. Therefore, energy wastages, primarily resulting from idle listening, collision, packet overhead, and overhearing, should be mitigated [10].

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MAC designs using contention technique, e.g., IEEE 802.15.4 MAC [3] and the protocol introduced in [8], incur collision, idle listening, and overhearing, and therefore introduce large power consumption. In TDMA-based MAC protocols [4–7], dedicated slots allocation naturally avoids such problems. However, synchronization overhead consume extra energy in beacon-enabled designs [3, 4, 6]. Therefore, synchronization scheme should be carefully designed in such protocols. A synchronization scheme using heartbeat rhythm information is proposed in [7], but heartbeat may not always reveal valid synchronization information because human conditions vary with time. Marinkovic *et al.* [5] proposed a synchronization scheme, where nodes can wait for a fixed maximum number of TDMA periods before resynchronization.

Heterogeneous and Dynamic Traffic

A WBAN is a heterogeneous system, where different types of sensors collect life and environment parameters. MAC protocols for WBAN should take into account the different demands, in terms of data rate and latency, of heterogeneous sensors. For example, nodes' data rate ranges from a few kb/s up to 10Mbps and thus their transmissions should be appropriately controlled to avoid data overload and intolerant latency. When WBAN context, i.e., human's activity or external environment, changes suddenly, it is essential that the most critical data can be delivered in a real-time fashion during such emergency context. Throughput and latency requirements of other data, however, can be relaxed. Therefore, WBAN MAC should also support dynamic resource allocation according to variable traffic nature. For example as shown in Fig. 2, all kinds of life parameters could be transmitted in a stable manner in normal context such as walking. However, one is likely to experience a blackout and ultimately a fall when abruptly sitting down or standing up. The transmission rate of blood pressure, hence, should be increased whereas transmission of EEG can be eliminated as shown in Fig. 2.

MAC protocols with fixed slots allocation [5, 7] cannot fulfill the need of heterogeneous and dynamic traffic of WBAN. Although alarm is supported in [4], it can only be processed when no node is scheduled, which constrains the response to emergency. In [6], the wakeup signal can make nodes switch from sleep to active state and help resource allocation when emergency events happen. However, an extra wakeup circuit is added in traditional nodes, which introduces high complexity and cost of hardware implementation. In [8], an attempt to build a context-aware WBAN is carried out. However, sensors lack the computational ability to recognize contexts, which is complex analysis rather than the simple out of bound computation. Thereby, the emergency interrupt triggered by sensors is impractical. Although 802.15.4 MAC supports seven GTS for contention-free transmission, the limited number of slots may not be sufficient when WBAN traffic is high, especially during the emergency context. Consequently, critical nodes sometimes have to contend with non-critical nodes in CAP, which incurs larger delay and overhead.

Fading Channel

In WBAN, wireless channel is usually considered as fading channel [2]. Transmitted signals can experience fading because context variation, such as frequent movements and variable body posture, may lead to reflection, diffraction, shadowing by body. The other possible reason for fading is the propagated signals can be absorbed by human body [1]. Channel measurements have shown that received power can fade below the receiver sensitivity for the duration of 10–400ms [2], which is much longer than traditional wireless networks. Besides, the percentage of time in such deep fading can reach 5.2 percent [2]. Therefore, fading needs to be considered for WBAN MAC design in order to ensure reliability.

TDMA-based MAC protocols [4–7] cannot handle the fading problem. In such designs, a node obtains continuous slots allocation and packets are transmitted back by back. If a packet is dropped due to deep fading, then the subsequent retransmission will, most probably, fail again since deep fading usually lasts for 10-400ms, during which multiple packets may have been scheduled for transmission by WBAN radio [2]. Hence, packets sent by the node may undergo consecutive drop and simple retransmission is difficult to recover all dropped packets. One possible solution is to interleave the packets from nodes/links. This way, when a node regains its opportunity of transmission after a transmission failure, the channel condition may improve and so retransmission may be successful. Contention-based designs own such nature because the contention channel will not always be accessed by one node thanks to random access mechanism. However, the hybrid 802.15.4 MAC and the contention-based protocol in [8] do not consider fading for MAC design. Thus the potential benefit brought by contention is not utilized

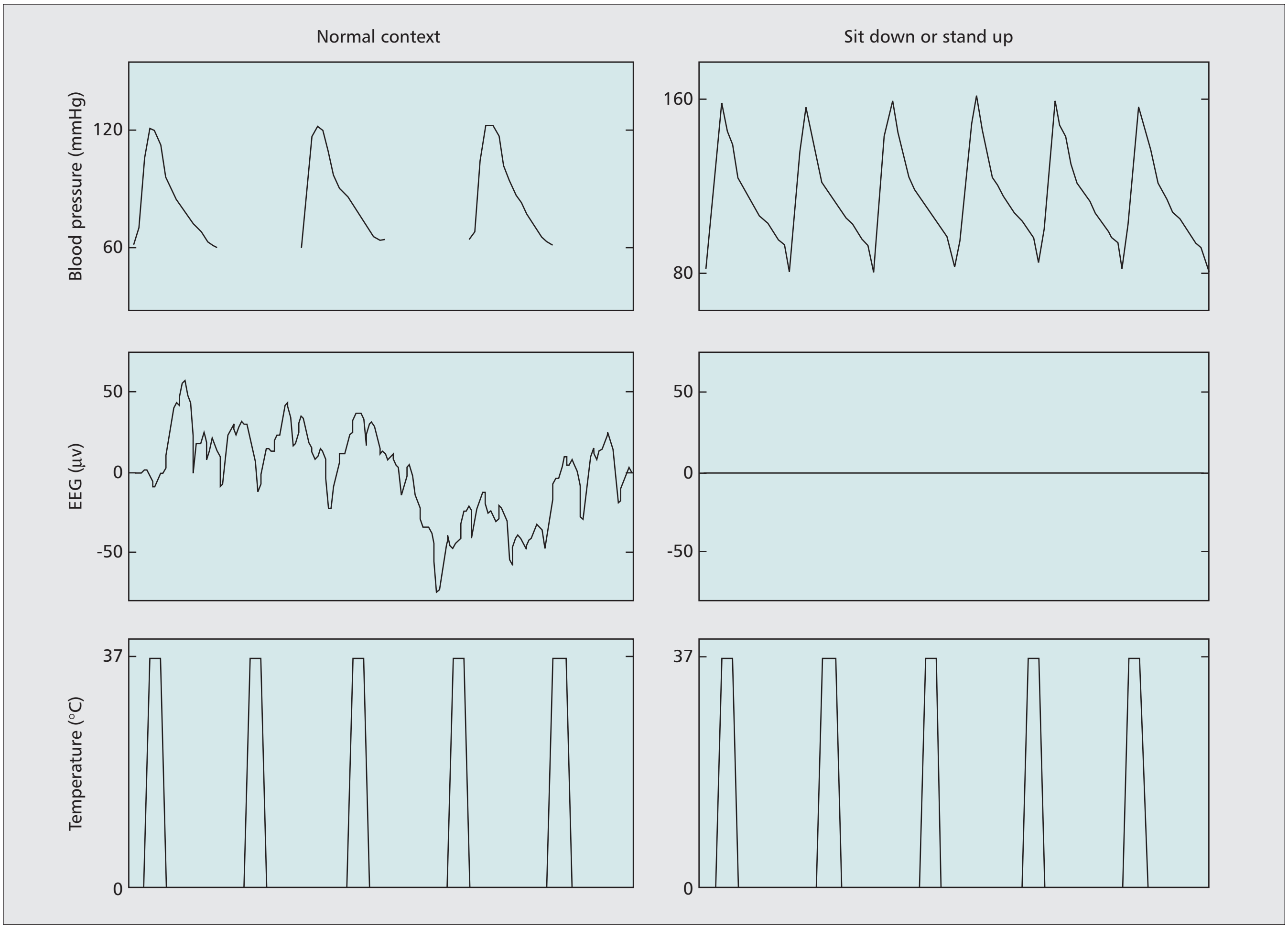

Figure 2. *Dynamic life signals transmission of normal context and sit down or stand up.*

and the contention of such protocols would even cause inefficiency since no tradeoff between reliability and efficiency can be made.

In summary, in order to deal with the challenges in energy efficiency, traffic demands and fading channel in WBAN, the combination of contention-based MAC with TDMA-based MAC is more appropriate so as to take advantage of desired features from both designs. However, a tradeoff between transmission reliability and efficiency needs to be carefully made according to time-varying WBAN context.

Context-Aware MAC Protocol Design

In this section, we present a context-aware MAC (CA-MAC) protocol, taking into account various issues not comprehensively addressed in the existing works. We first introduce the hybrid superframe structure of CA-MAC. Then we describe the traffic-aware adjustment of transmission priority and channel-aware adjustment of access mechanisms. The combination of traffic-aware and channel-aware adjustment leads to desired efficiency and reliability. The comparisons between CA-MAC and existing works are summarized in Table 1. We also compare the performance of CA-MAC with that of IEEE 802.15.4 MAC [3] and H-MAC [7] to show the advantages of CA-MAC.

Hybrid Superframe Structure

As shown in Fig. 3a, a new hybrid contention/TDMA superframe structure is proposed, which consists of three parts: beacon, contention, and TDMA. The superframe and the beacon both have constant duration. However, the duration allocated to contention or TDMA part can be adaptively changed.

In the first superframe, a beacon packet is broadcasted by the coordinator to synchronize nodes and establish communication links. Then if WBAN context (traffic or channel condition) changes, beacon packets are broadcasted to specify the new superframe structure. For example, the TDMA slot allocation and how long contention part will last are given at this period. Since the context analysis is completed by the coordinator, most computation can be removed from sensors.

In the following contention part, slotted CSMA/CA random access mechanism is adopted. As we previously mentioned, contention-based mechanism has the advantage of mitigating the deep fading problem. By using the proposed algorithm, moreover, the duration of contention part is dynamically configured according to the extent to which the WBAN is impacted by fading. Detailed descriptions of the channel-aware mechanism will be given later.

	Energy Efficiency	Dynamic Traffic	Fading Channel
IEEE 802.15.4 MAC [3]	Large collisions; high synchronization overhead.	Not suitable to heterogeneous and variable traffic since only limited number of GTS is supported.	Possible to handle fading but fading is not considered; thus inefficient contention with no tradeoff.
MAC in [4]	Collisions avoidance; high synchronization overhead.	Not suitable to heterogeneous and variable traffic since an alarm is supported only when there is no scheduled node.	Easy to experience consecutive packet loss due to TDMA-based design.
MAC in [5]	Collisions avoidance; low synchronization overhead using optional synchronization.	Not suitable to heterogeneous and variable traffic due to fixed slot allocation for every node.	Simple retransmission using RSn slots; still easy to experience consecutive packet loss due to TDMA-based design.
MAC in [6]	Collisions avoidance; high synchronization overhead.	Good for variable traffic due to wakeup strategies; but high complexity and cost caused by extra hardware.	Easy to experience consecutive packet loss due to TDMA-based design.
H-MAC [7]	Collisions avoidance; low synchronization overhead using heartbeat rhythm.	Not suitable to heterogeneous and variable traffic due to fixed slot allocation for every node.	Easy to experience consecutive packet loss due to TDMA-based design.
FrameComm MAC [8]	Large collisions; no synchronization overhead.	Good for variable traffic due to interrupt scheme for high priority nodes; but impractical due to emergency triggered by sensor nodes.	Possible to handle fading but fading is not considered; thus inefficient contention with no tradeoff.
CA-MAC	Collisions avoidance; low synchronization overhead using optional synchronization.	Good for variable traffic due to dynamic scheduled-based and polling-based slots allocation; nodes can obtain requested slots in current frame.	Good for fading channel due to dynamic adjustment of contention period.

Table 1. *Comparisons between existing works and CA-MAC.*

There are two subparts in the contention-free TDMA part, i.e., schedule-based slots and polling-based slots. Schedule-based slots are dynamically reserved for nodes based on traffic nature. With a period of one superframe or multiple superframes, nodes periodically wake up and transmit data in their scheduled slots. However, polling-based slots are usually inactive with no transmission and only assigned to particular nodes on demand in the current superframe. Only when emergency occurs, these slots can be allocated by the coordinator through the poll messages. The time interval between two slots, called guard time period, is reserved for the proposed synchronization scheme, where nodes only synchronize through ACK when timing errors cause slot overlapping and thereby have no need to receive synchronization information in every superframe.

Traffic-aware Adjustment of Transmission Priority

Within a specific WBAN context, sensory data that are most relevant to monitoring and diagnosis need to be delivered with acceptable data rate and latency. To satisfy this requirement, CA-MAC dynamically changes the sampling rate and scheduled-based slots of each type of sensors. Besides, a new polling-based access scheme is designed to manage time-critical contexts. We illustrate such adjustment in Fig. 3b.

Under normal context, a node transmits data to the coordinator in its allocated schedule-based slots. When data transmission is completed within the allocated slots or the sender buffer is empty (with no packet to send), the node should enter sleep state for the purpose of saving energy. Then at the beginning of a new superframe, all the nodes wake up in order to check whether a new beacon packet is broadcasted. If nodes fail to sense the beacon, they go back to sleep until the next allocated transmission comes. The superframe structure remains fixed if a new beacon packet is not broadcasted by the coordinator. If nodes receive a newly broadcasted beacon, however, it indicates the coordinator has detected abnormalities through data analysis during the previous superframe and needs to trigger the emergency context. Thus nodes are able to extract the updated sampling rate and slot allocation from the beacon. An updated structure of superframe is shaped accordingly. Sensors that are of most relevance to the context reserve more transmission slots. Meanwhile, their sampling rate is also increased to satisfy the emergency data rate requirement. Other irrelevant sensors, nevertheless, might reduce reserved slots and sampling rate, or even end their data delivery, contributing to reducing energy consumption. The emergency context continues until the coordinator transmits another beacon triggering the WBAN's return to normal context.

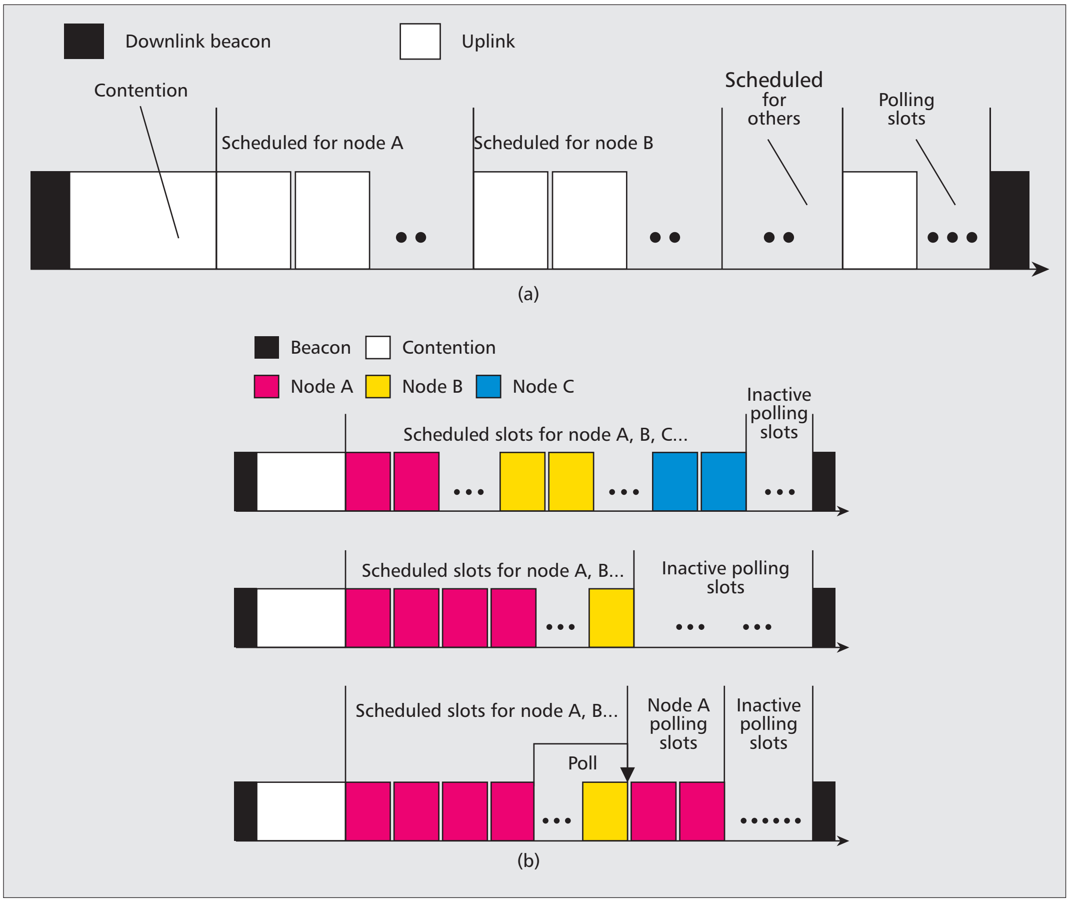

Figure 3. *a) CA-MAC superframe structure; b) traffic-aware adjustment of TDMA slots based on superframe structure.*

Within a specific WBAN context, sensory data that are most relevant to monitoring and diagnosis need to be delivered with acceptable data rate and latency. To satisfy this requirement, CA-MAC dynamically changes the sampling rate and scheduled-based slots of each type of sensors.

We utilize a novel scheme to allocate polling-based slots. When receiving packets from a sensor node, the coordinator counts the number of packets indicating the sender has one extra packet to transmit. Then the coordinator replies a poll message embedded in the ACK at the last schedule-based slot of this node in order to allocate polling-based slots. The poll message incorporates when to start the polling-based slots and the amount of polling-based slots allocated to that node. This way, particular nodes could quickly obtain requested polling-based slots in the current superframe.

We compare the latency and power consumption performance of CA-MAC with 802.15.4 MAC [3] and H-MAC [7]. The simulation scenario contains one coordinator and twenty sensors which are equally partitioned into A, B, C, and D four groups. We assume group A and B sample the most important data during this monitoring. Besides, during the emergency context, nodes from group C powers off the radio and nodes from group D shall fix their reserved slots and sampling rate. We assume the coordinator detects emergency at 180th second and the duration of emergency context is 220 seconds. When simulating 802.15.4 MAC, we use beacon-enabled version with complete GTSs. The temporal average of packet latency with increasing time is shown in Fig. 4a. CA-MAC outperforms 802.15.4 MAC and H-MAC, especially during the emergency context, since CA-MAC reallocates the transmission slots of nodes according to context information, i.e., traffic nature. Thus critical nodes can transmit more packets per unit time, which reduces the average packet latency. When using 802.15.4 MAC, nevertheless, nodes in group A and B have to compete with those unconcerned nodes during CAP, which introduces large latency. Although H-MAC achieves the same latency as CA-MAC at first due to the initial slot allocation, its fixed slot assignment is inefficient when traffic varies. For example, group A and B fail to obtain more slots in emergency context and thus some of the critical data are continuously buffered, which results in the continuously increasing latency. In CA-MAC, since low latency is achieved at the cost of extra energy consumption for critical data transmission, evaluation of energy consumption is needed.

The energy efficiency comparison is shown in Fig. 4b, where we use average power consumption per kilo bits as the performance metric. The bar chart represents the performance of overall system and each group of nodes. Although seven GTSs are adopted by 802.15.4 MAC for energy saving purpose, CA-MAC still demonstrates a superior performance. This is attributed to the fact that the contention-free slot allocation and periodic wake up and sleep mechanism of TDMA access reduce the power consumption. Accordingly, energy consumptions resulted from more transmission of critical data and sensing of

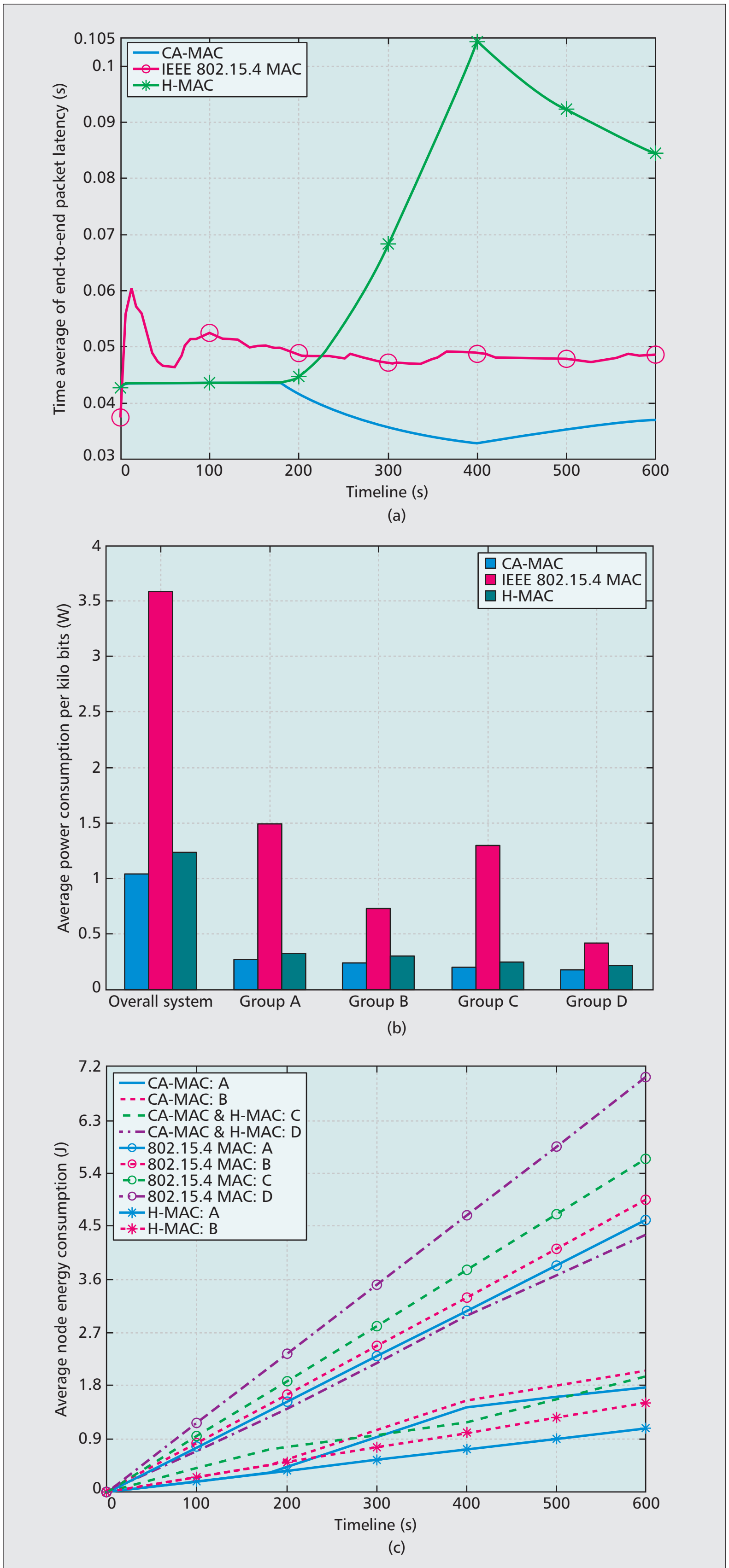

Figure 4. *a) Time average of packet latency as a function of time adopting CA-MAC, 802.15.4 MAC, and H-MAC; b) bar chart comparing average power consumption of CA-MAC, 802.15.4 MAC, and H MAC (from left to right); c) average node energy consumption as a function of time adopting CA-MAC, 802.15.4 MAC, and H-MAC.*

beacon packets are well compensated. In the WBAN adopting 802.15.4 MAC, however, nodes suffer collisions due to CSMA/CA access and therefore waste more energy because of retransmissions. We also observe that H-MAC has a comparable performance as CA-MAC. However, it is important to note that most of the received packets are actually delayed when using H-MAC, which means they may become useless then. To highlight the energy saving contribution of context-aware adjustment in CA-MAC, we show the average node energy consumption of different groups in Fig. 4c. In CA-MAC, the energy consumption of group A and B that collect critical data increases relatively fast during emergency context. This is because group A and B generate more data and get more slots for transmission in emergency context. Similarly, group C and D that are less important consume energy with a reduced and constant speed during emergency context, respectively. Nevertheless, the energy consumption of 802.15.4 MAC increases constantly and shows a less efficient performance because its resource allocation is fixed. Besides, the less energy consumed by group A and B in H-MAC is achieved by sacrificing the amount of transmitted data. This is unacceptable since the emergency monitoring can be negatively impacted.

Channel-Aware Adjustment of Access Mechanisms

We have mentioned the significant impact of fading in TDMA-based designs and the inherent advantage of contention-based designs to deal with fading. Hence, we incorporate the contention part using CSMA/CA to handle fading. In CSMA/CA, a sensor first backs off a random period before sensing the channel. If the channel is idle after the sensing, the sensor starts to transmit data in the next slot. If the channel is busy, however, the sensor backs off another period before trying to retransmit. This procedure continues until the node successfully transmits a packet or the maximum bound of backoff times is reached. Hence, a node has to experience random backoff at least once. When a node suffers from deep fading and then transmission failure, its retransmission shall be postponed due to the random backoff mechanism in CSMA/CA. Consequently, another node with idle channel is more likely to win the subsequent transmission opportunity. The winning node usually owns a higher probability to successfully transmit a packet thanks to its relatively good channel condition. When the previously failed sensor regains its transmission opportunity, such retransmissions could also become successful since the impact of fading might be lessened or eliminated then. This way, the packet loss rate of WBAN is decreased and the transmission reliability is enhanced.

However, the idea of interleave the transmissions from nodes/links by using contention increases reliability at the cost of collision among nodes. We cannot simply keep increasing the duration of contention period. Rather, we should execute a deliberate tradeoff between collision and transmission reliability. In this research, we define NCDP as the number of consecutively

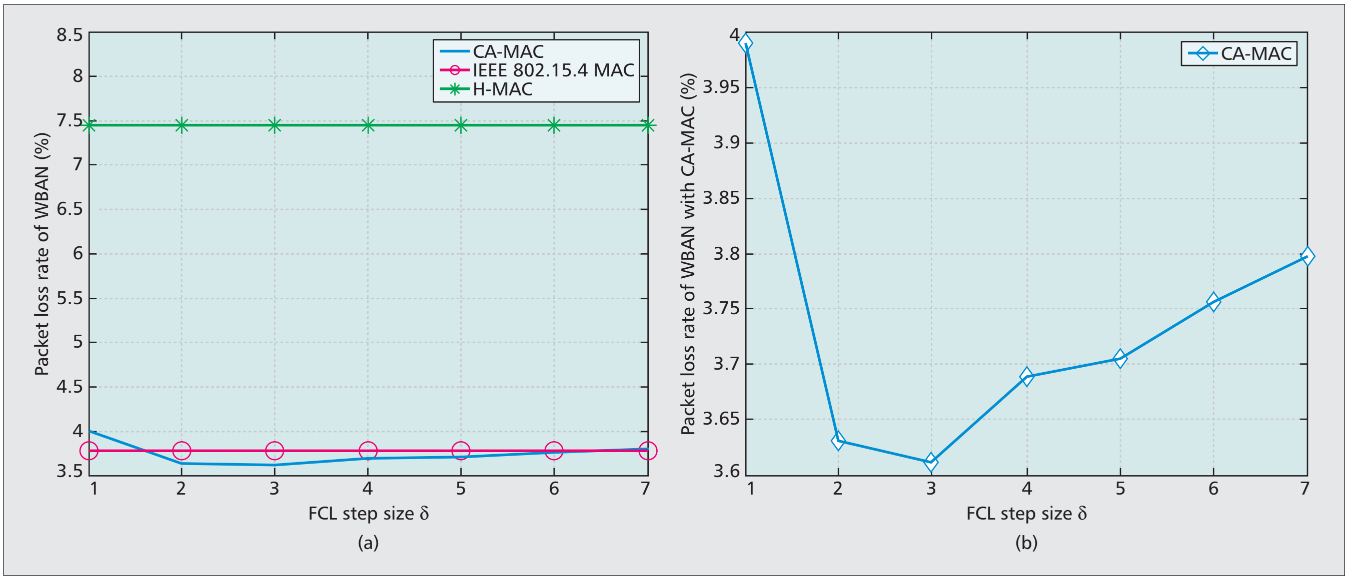

Figure 5. *a) Packet loss rate of WBAN adopting CA-MAC, 802.15.4 MAC, and H-MAC versus FCL step size δ; b) packet loss rate of WBAN adopting CA-MAC versus FCL step size δ.*

dropped packets from one node and TDC as the total times of data collision among nodes. Then, we define the contention length index (CLI) as the ratio between NCDP and TDC in order to set up the contention operation appropriately. As one single packet may be dropped because of errors at a receiver, deep fading is characterized by at least two consecutively dropped packets of one node in this research. A larger NCDP indicates worse channel condition and thus increases CLI. A larger TDC indicates more collisions caused by CSMA/CA and thus decreases CLI.

Initially, the duration of contention period is set to an extremely short value, e.g., one slot in this research, so as to keep the integrity of superframe structure. During a superframe, the coordinator calculates each node's NCDP and the WBAN's TDC through analyzing data transmission within the system. The coordinator then determines the final contention length (FCL) of next superframe on the basis of the average node CLI (ACLI) in the current superframe. If ACLI is slightly higher or lower than ACLI of the previous superframe ($ACLI_{pre}$), indicating current WBAN context (channel condition) is relatively stable, FCL should stay fixed. The lower bound and upper bound is denoted by β*ACLIpre and α*ACLIpre, respectively. If the channel condition improves or deteriorates substantially, i.e., ACLI is out of the bounded range, FCL would be decreased or increased with a step size of δ slots in order to adapt to the fluctuation of contexts.

The coordinator then encapsulates this new FCL into a beacon and broadcasts the packet at the beginning of next superframe. This way, the overall packet loss rate can be reduced by introducing longer contention part when channel condition becomes worse. Besides, the energy efficiency can be enhanced by decreasing contention part when fading problem is mitigated. Such channel-aware adjustment strategy enhances the transmission reliability while keeping the collision in a reasonable amount.

We evaluate the packet loss rate of the WBAN of CA-MAC, compared with 802.15.4 MAC and H-MAC. We simulate a star-topology WBAN that consists of three sensor nodes and one coordinator. To characterize the complicated on-body channel with time-varying fading, several random periods during the simulation is chosen as deep fading. The average deep fading duration of three nodes' link is 50ms, 30ms, and 40ms, respectively. The percentage of time in deep fading for three nodes' link is 5 percent, 2.5 percent, and 0.5 percent, respectively. Simulation parameters are set based on the work of Boulis *et al.* [9] and 802.15.4 MAC. For a smooth adjustment of contention length, we set α as 1.5 and β as 0.7 based on extensive simulations. The contention part of CA-MAC is adaptively changed whereas the TDMA-based slots are equally allocated to three nodes. When implementing the reference protocols, the same superframe length is adopted. Besides, each node reserves one third of the total contention-free slots.

In Fig. 5a, we show the trend of packet loss rate with increasing FCL step size δ. CA-MAC achieves a packet loss rate between 3.61 percent and 3.99 percent, which is about 50 percent lower than that of H-MAC (fixed at 7.45 percent). This is attributed to the fact that CA-MAC redistributes transmission attempts of one node to several other nodes by utilizing contention access. Thereby, those sensors that have good channel condition while other sensors are experiencing deep fading may win the opportunities of transmission. Thus the overall packet loss rate can be decreased. Nevertheless, in H-MAC using TDMA-based access, sensors always fail to deliver packets if the assigned slots are in deep fading, which negatively impacts the overall transmission reliability. Although the packet loss rate of 802.15.4 MAC is not much larger than that of CA-MAC due to its default contention period, its contention duration cannot be adapted to channel condition. Therefore, the fixed and long contention period leads to longer delay and extra energy consumption, as shown in Fig. 4.

Future work shall be focused on involving more contextual parameters, such as inter-WBAN interference and remaining energy, into this context-aware MAC design in order to meet various body conditions and surrounding environment.

To discuss the interesting trend of how CA-MAC's packet loss rate varies with respect to δ, we only show CA-MAC's results in Fig. 5b. We observe that the packet loss rate drops down to a lowest point when δ increases from 1 to 3. As was explained previously, when deep fading happens in current superframe, the next superframe with longer contention period brings about less dropped packets than that with shorter contention period. Therefore, when using a larger δ, the duration of contention period would increase faster. Accordingly, the WBAN will spend less time in the vulnerable state that has many TDMA slots and can manage channel variation better. The number of lost packets is hence relatively small. However, the packet loss rate returns to a relatively high level when the step size keeps increasing. Such trend can be explained as follows. Although larger δ may lead to larger average contention part and less packet loss, the decrease in total amount of successfully transmitted packets caused by less TDMA-based slots may contribute to the increase in packet loss rate.

Conclusion

We have addressed in this research two key factors that impact the performance of WBAN: efficiency and reliability. Since we usually deal with single-hop communication in resource-limited WBAN, MAC protocols, which ensure proper channel access control and reliable link-level communication, should be carefully designed. In this article, we report our investigation on how the variable contexts of WBAN can influence its performance and how this feature can challenge the MAC design. Several MAC challenges and their potential proposals are discussed. We present a hybrid context-aware MAC protocol to overcome challenges in limited energy, time-varying traffic, and complicated channel in WBAN. With dynamic adaptation of MAC superframe structure based on channel status and traffic nature, nodes can use proper access mechanism, transmission duration, and sampling rate to transmit data in order to achieve both transmission efficiency and reliability. The proposed protocol outperforms traditional non-context-aware MAC and strike a desired trade-off between efficiency and reliability. Future work shall be focused on involving more contextual parameters, such as inter-WBAN interference and remaining energy, into this context-aware MAC design in order to meet various body conditions and surrounding environment. Furthermore, cross-layer design will also be pursued to achieve an optimal tradeoff between QoS and energy consumption in WBAN.

Acknowledgment

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