CA-MAC: A Hybrid Context-aware MAC Protocol for Wireless Body Area Networks

Bin Liu and Zhisheng Yan
School of Information Science and Technology
University of Science and Technology of China
Hefei, Anhui, 230027, P. R. China
flowice@ustc.edu.cn, zsyan@mail.ustc.edu.cn

Chang Wen Chen
Computer Science and Engineering Department
University at Buffalo, the State University of New York
Buffalo, NY, 14260-2000 USA
chencw@buffalo.edu

Abstract—**In wireless body area network (WBAN), various data sources are generated by different type of sensors and transmitted to the master node, which may result in temporally different traffic loads. With time-varying channel caused by frequent body movement, transmitted data may also experience deep fading and packet loss. To meet the complex transmission requirements in WBAN, a traffic-aware and channel-aware MAC protocol is required. In this paper, we introduce CA-MAC, a context-aware MAC protocol using a hybrid of contention-based and TDMA-based approaches. A dynamic control mechanism is proposed to address fading channel by adaptively modifying MAC frame structure. Schedule-based and polling-based techniques are also used to manage periodic, bursty, and emergency traffic requirement. Simulation results confirm the advantage of CA-MAC on reliability over existing TDMA-based approach.**

Keywords-Context Aware; Hybrid; MAC; WBAN

I. INTRODUCTION

Wireless body area network (WBAN) is a body-centric system which consists of body-worn sensors, implanted sensors, and master node. Sensor nodes collect various kinds of information in or around human body and transmit data to master node for further processing. To meet the challenges on network quality such as throughput, latency, energy and data reliability, proper channel access and resource allocation mechanism are very much needed. Hence, designing an efficient MAC protocol has become an imperative task.

In ubiquitous WBAN environment, sensor nodes may request different channel resources under different scenarios. For example, within the monitoring context of a cardiopathy patient, many vital signs could be transmitted at the same priority for daily data collection. When the patient is doing exercise and suffers from potential danger to his/her health, heart rate and ECG signals are most time-critical and should be transmitted in a real-time manner. In such scenario, real-time transmission of other unconcerned data, e.g., blood glucose or EEG signals, is usually not necessary. Therefore, in order to satisfy the varying requirements of WBAN, a context-aware MAC protocol is needed to adopt different transmission strategies for sensor nodes, according to the variation of some contextual information, such as parameters about one's activity or environmental status.

TDMA-based MAC and contention-based MAC are known as two basic channel access mechanisms for wireless sensor network (WSN). Recently, some MAC protocols [2-4] have been proposed for WBAN on the basis of these two techniques. However, they lack the adaptability to varying traffic needs and the ability to switching between transmission strategies in accordance with different contexts. Considering the requirement of context awareness in WBAN, researchers are trying to apply adaptive variation of transmission priority in MAC protocols to meet the changing traffic requests of sensor nodes. T. O'Donovan *et al*. [5] carried out a preliminary attempt to build a context-aware MAC protocol by proposing a novel interrupt approach to enable real-time transmission of important data. However, its contention-based access mechanism may incur serious collision. Besides, the change of contexts triggered by the sensors cannot be easily implemented in reality. In our previous work [6], we proposed a TDMA-based MAC protocol with the ability of context awareness. We utilize dynamic slots allocation and a novel synchronization scheme to reduce energy consumption and latency.

TDMA-based approach is usually more efficient in star-topology WBAN than contention-based approach. However, complex time-varying channel in WBAN caused by frequent body movements is not considered in the design of TDMA-based MAC protocol. Transmitted data may sometimes undergo deep fading and cannot be detected by the receiver if the received signal strength is below the receiver sensitivity. Deep fading usually lasts for 10-50ms, during which several packets can be transmitted. In TDMA-based design with continuous slots allocation, packets from one sensor may experience consecutive loss and simple retransmission mechanism is difficult to recover all these lost packets. Furthermore, the control messages, e.g., beacon or synchronization packets, become vulnerable, which may lead to wastage of reserved channel resources. Nevertheless, contention-based design owns the inherent nature to timely spread transmission opportunity of a sensor node. The contention channel will not always be connected to one sensor attributed by random access mechanism. Thus packets for retransmission are less likely to experience deep fading comparing with those in TDMA-based design. Therefore, such scheme mitigates the impact of complex channel environment. Some researchers have tried to combine TDMA and contention. Both BodyMAC [7] and the work of Y. Zhang *et al*. [8] are different variations over IEEE 802.15.4 MAC. However, they do not consider the deep fading in WBAN channel. A. Boulis *et al*. [9] study the effects of contention and polling in the WBAN MAC design and provide some suggestions.

To the best knowledge of the authors, there are no MAC protocols for WBAN that adopts context awareness in terms of both traffic nature and channel status, namely the protocol is both traffic-aware and channel-aware. In this paper, we propose CA-MAC, a context-aware hybrid TDMA and contention MAC protocol for star-topology WBAN. The context awareness built in CA-MAC is based on both channel-aware and traffic-aware functions. Since contention-based MAC has a natural feature to handle packet loss caused by deep fading, we combine contention-based MAC with TDMA-based MAC to ensure reliable data transmission at the expense of incurring tolerable collisions. Dynamic adjustment of channel access mechanism using channel information can significantly increase the probability of successful retransmission and reduce the packet loss rate. Additionally, master node adaptively alters the transmission priority of sensor nodes. Based on traffic requests of sensor nodes, TDMA slots are assigned to them in a most efficient way. Therefore, sensor nodes with high priority can access the channel faster and transmit more data whereas unnecessary transmissions can be restricted.

The rest of the paper is organized as follows. In Section II, we describe the details of the proposed CA-MAC design, including design for adaptive channel access and resource allocation. Simulation results and performance evaluation are given in Section III. Finally we conclude this paper in Section IV.

II. CA-MAC DESIGN

A. Frame Structure

In CA-MAC, we design a new hybrid contention/TDMA MAC frame structure, which is shown in Fig. 1, to accomplish channel awareness and traffic awareness. It composes of beacon, contention part, and TDMA part. The length of beacon and the whole frame is fixed but the proportion that contention part or TDMA part occupies is changed adaptively.

Master node sends a beacon packet to all sensor nodes for initial synchronization and establishment of communication link in the first frame. Then beacon packets are broadcast to define the frame structure in every frame. For instance, the length of contention part and TDMA slot allocation will be given at this stage.

The following contention part, which adopts slotted CSMA/CA random access mechanism, has a variable length depending on wireless channel status. As we mentioned in the previous section, contention-based mechanism is good at coping with deep fading. Hence, based on the extent to which

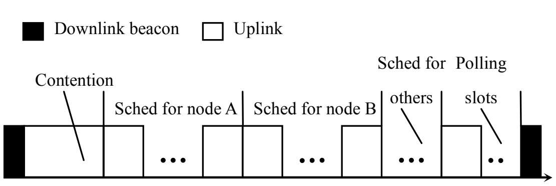

Figure 1. CA-MAC frame structure.

the WBAN suffers from fading, the length of contention part is set accordingly. If channel condition is good enough for regular transmission, contention part is cut down to an extremely short period for the sake of energy efficiency.

The TDMA part, which is for contention-free data transmission, is further divided into two subparts: schedule-based slots and polling-based slots. Schedule-based slots are dynamically reserved to sensor nodes based on traffic requirements. In these slots, sensor nodes periodically send collected data with a period of one frame or multiple frames. The polling-based slots, which are usually inactive with no transmission, are assigned to specific sensor nodes on demand in the current frame. Mater node allocates these slots through the poll messages only if emergency traffic occurs.

B. Channel-aware Adjustment of Access Mechanisms

In the TDMA slots, data packets from one sensor may be transmitted continuously. Thus, repeated packet loss due to deep fading is easily found. When a packet fails to be transmitted in a slot, retransmission in the following slots may also be unsuccessful due to bursty nature of channel. Therefore, in our CA-MAC design, we include contention part to mitigate such problem. In contention part, when a sensor node fails to transmit a packet caused by deep fading, random backoff mechanism in CSMA/CA shall postpone its retransmission. As a result, another idle sensor is more likely to win the subsequent opportunity of channel access. The winning sensor usually has a better chance of successful transmission due to its relatively good channel condition. Retransmission of the previously failed senor may now become successful because the impact of deep fading may be lessened or eliminated when this sensor regain its transmission opportunity. In this way, we are able to decrease the packet loss rate and increase the transmission reliability.

Nevertheless, the idea of timely spreading transmission through contention brings about benefits at the expense of data collision among sensor nodes. We cannot simply keep increasing the length of contention part because of data collision. Rather, we need to make a deliberate tradeoff between transmission reliability and data collision. In CA-MAC, we define contention length index (*CLI*) to set up contention part appropriately. This parameter is formulated as

$$CLI_i = \frac{NCDP_i}{TDC} \quad (1)$$

where *i* refers to the sensor index. Here *NCDP* is defined as the number of consecutively dropped packets from one sensor node. As single dropped packet may happen due to receiver error, deep fading is denoted by at least two continuous dropped packets in this paper. A larger *NCDP* means worse channel condition and may increase *CLI*. *TDC* represents the times of data collision among all sensor nodes. A larger *TDC* means more collision resulted from CSMA/CA and may decrease *CLI*.

The length of contention part is dynamically modified as follows. The contention part is initially set to an extremely short period, e.g., one slot in this research in order to guarantee the integrity of frame structure. *CLI* has a value of zero initially when the network starts to work. Then master node counts the value of *NCDP* for each sensor and the value of *TDC* by analyzing data transmission in the network. Within one frame, *CLI* is calculated for each node using (1). Master node thus can determine the final contention length (*FCL*) of next frame based on the average *CLI* (*ACLI*) of senor nodes as follows,

$$ACLI = \frac{1}{N}\sum_{i} CLI_i \quad (2)$$

Master node is also required to take into account *ACLI* in previous frame ($ACLI_{pre}$). If current *ACLI* is slightly higher or lower than $ACLI_{pre}$, this indicates that current channel condition is relatively stable, hence *FCL* should remain unchanged. The upper bound and lower bound is denoted by $\alpha^* ACLI_{pre}$ and $\beta^* ACLI_{pre}$ respectively. If *ACLI* differs substantially from $ACLI_{pre}$, i.e., higher than $\alpha^* ACLI_{pre}$ or lower than $\beta^* ACLI_{pre}$, *FCL* will be increased or decreased with a step size of δ slots to adaptively satisfy the fluctuation of network condition. *FCL* cannot exceed the maximum and minimum bound of *FCL*, which are denoted as FCL_{max} and FCL_{min}. We can set and optimize the value of α, β, δ, FCL_{max}, and FCL_{min} in accordance to the extent of deep fading. The new *FCL* is calculated according to (3),

$$\begin{cases} FCL=\min(FCL_{max}, FCL+\delta), & ACLI>\alpha * ACLI_{pre} \\ FCL=FCL, & \beta * ACLI_{pre} \le ACLI \le \alpha * ACLI_{pre} \\ FCL=\max(FCL_{min}, FCL-\delta), & ACLI<\beta * ACLI_{pre} \\ \alpha>1,\ 0<\beta<1 \end{cases} \quad (3)$$

Thus, *FCL* can change smoothly as channel varies.

This new *FCL* is then encapsulated into a beacon packet and broadcasted by master node at the beginning of next frame. In this way, sensor nodes may experience longer contention period to reduce packet loss rate when channel fading becomes more serious. They can spend less time in contention for energy efficiency when channel condition improves. This channel-aware adjustment of access mechanism increases the possibility of successful transmission and also decreases the data collision in an efficient way.

C. Traffic-aware Adjustment of Transmission Priority

In WBAN, sensor nodes may differ in their transmission requirement when one carries out different activities. In our CA-MAC design, the transmission bandwidth and sampling rate of sensors are dynamically configured to satisfy the changing traffic demand. The adjustment strategy is shown in Fig. 2.

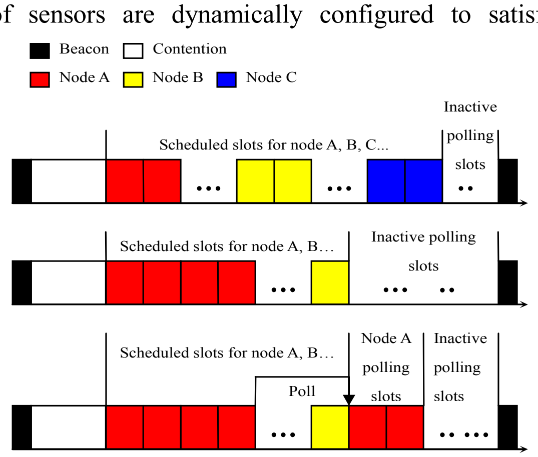

Figure 2. Traffic-aware adjustment of TDMA slots.

Schedule-based TDMA slots are designed to deal with periodic traffic. Sensor nodes work in their assigned slots respectively. They power off and return to sleep at the respective idle slots to avoid collision and to increase channel utilization. If master node detects some context variation in WBAN by data processing and analysis, e.g., when the patient under monitoring falls, it triggers an emergency state and broadcasts a new beacon packet with new slots allocation at the next frame. Then all sensor nodes take the updated information about slot allocation and a new frame structure is formed. Those sensor nodes which are most relevant to the monitoring context obtain higher duty cycle, which implies more slots for transmitting data. At the same time, these nodes may also increase their sample rate to fulfill emergency monitoring task. Other unconcerned nodes, however, may release available bandwidth and reduce sample rate, or even cease data transmission, resulting in reduction of energy wastage. The emergency state lasts until master node broadcasts another new beacon packet altering the system to return to normal state. In our previous work [6], we have shown that this traffic-aware allocation of scheduled-based slots has significant improvement on latency and energy, compared with IEEE 802.15.4 MAC.

To manage time-critical applications, we design a new polling-based TDMA access mechanism. It utilizes the moreData field which is supported by MAC and security baseline proposal [1] of IEEE 802.15.6 task group. If master node receives a packet whose moreData field is set to 1, it means the node sending this packet has one extra packet to transmit. Master node counts the number of such packets. At the last schedule-based slot of this sensor node, master node replies a poll message encapsulated in the ACK packet. By sending the poll message with the counting value, proper amount of slots are assigned to that node. The starting slot is also incorporated in the poll message. Hence, individual nodes can get required polling-based slots based on their own need in every frame.

III. SIMULATIONS AND PERFORMANCE EVALUATION

We compare the performance of the proposed CA-MAC with that of the context-aware TDMA-based MAC previously developed in [6] in terms of packet loss rate of the entire sensor network. The simulation is based on a star-topology model with one master node and three sensor nodes. Sensor nodes generate source data with a fixed sampling rate of 50kbps. Because there is no standard for physical layer of WBAN, the channel model of IEEE 802.15.4 will be utilized in the simulations. The wireless transceivers operate in 2.4 GHz band with data rate of 250kbps. To model the complex time-varying fading channel, we randomly choose several periods during simulation time as deep fading. Both time interval during which the received signal is below receiver sensitivity and the frequency of deep fading are used to signify the extent of fading. Parameters of simulations are configured based on IEEE 802.15.4 MAC and the work of A. Boulis [9]. Details are given in Table I.

TABLE I: DETAILED PARAMETERS FOR SIMULATIONS

Parameters	Value
Average Deep Fading Duration (node 1)	50ms
Average Deep Fading Duration (node 2)	30ms
Average Deep Fading Duration (node 3)	40ms
Percentage of Time in Deep Fading (node 1)	5%
Percentage of Time in Deep Fading (node 2)	2.5%
Percentage of Time in Deep Fading (node 3)	0.5%
Slot Length	7.68ms
Frame Length	122.88ms
FCL_{min}	1 slot
FCL_{max}	15 slots

The length of contention part is set to one slot when simulation begins, i.e., initial *FCL* equals to 1. When channel status varies, *FCL* can change smoothly between FCL_{min} and FCL_{max}. Consequently, the length of contention part can be dynamically modified to deal with fading channel and data collision properly. The rest of MAC frame using TDMA-based approach are equally divided into three portions and are assigned to three sensors respectively. To demonstrate the impact of *FCL* step size δ on determining *FCL* and packet loss rate, we compare the packet loss rate under different cases, where δ varies whereas the other two remain unchanged. When simulating the TDMA-based MAC, the same frame length and slot length are used. Each sensor always obtains one third of the overall slots resources to transmit data. The simulation runs five times and each one lasts 130 seconds.

We calculate the packet loss rate of network as a function of the *FCL* step size δ, with a fixed value of α=1.5 and β=0.7. The packet loss rate of CA-MAC (between 3.61% and 3.99%) is about 50 percent lower than that of TDMA MAC (fixed at 7.45%). This is because CA-MAC utilizes contention mechanism to redistribute transmissions of one sensor to several senor nodes. Sensor nodes with good channel conditions during other sensors' fading period may obtain transmission chance. Thus packet loss rate can be reduced. However, in TDMA MAC, sensor nodes always fail to transmit packets if their dedicated slots are in deep fading, which has a negative effect on reliability of sensor data transmission.

To explain the interesting trend of packet loss rate versus δ, we give the curve only with CA-MAC in Fig. 3. It can be seen from figure that the packet loss rate of CA-MAC drops down to a lowest point with δ increasing from 1 to 3. As stated before, when deep fading occurs in one frame, the next frame with larger contention part results in lower dropped packets than those with smaller contention part. Hence, with a larger δ, the

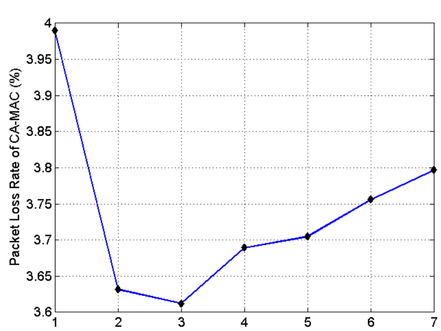

Figure 3. Packet loss rate of CA-MAC versus FCL step size δ.

length of contention part can be increased faster, which means the system can spend less time to manage channel variation. The number of dropped packets is therefore relatively small when handling fading channel. Nevertheless, the packet loss rate goes back to a relatively high level if δ continues to increase. This trend can be explained from the fact that the number of TDMA-based slots is reduced with a large δ. Although larger step size may lead to longer average contention period and less dropped packets, the decreasing amount of successfully transmitted packets may contribute to the increased packet loss rate. Accordingly, the packet loss rate continues to increase.

IV. CONCLUSION

We have developed a hybrid context-aware MAC protocol to overcome challenges resulting from time-varying traffic and channel conditions in WBAN. Master node dynamically modifies the structure of MAC frame based on both channel status and traffic request. By exploiting this strategy, sensor nodes can adopt proper access mechanism, transmission bandwidth, and sampling rate to send data for the purpose of both transmission reliability and efficiency. Simulation results show that CA-MAC reduce packet loss rate in WBAN and make a reasonable trade off between reliability and efficiency.

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