A Context Aware MAC Protocol for Medical Wireless Body Area Network

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Abstract—**During long-term medical monitoring in Wireless Body Area Networks (WBAN), network requirements (i.e. traffic loads and latency) of various data sources may be different at different time. High traffic loads may lead to data overload and unacceptable latency, which makes potential danger of patients undiagnosed. It is important that real-time transmission of life-critical data can be always guaranteed. To address this problem, a context-aware MAC protocol is presented in this paper. According to analysis of collected life parameters, the protocol can switch between normal state and emergency state. As a result, data rate and duty cycle of sensor nodes are dynamically changed to meet the requirement of latency and traffic loads in a context-aware way. To save the power consumption, a TDMA-based MAC frame structure is used. Moreover, a novel optional synchronization scheme is proposed to decrease the overhead caused by traditional TDMA synchronization scheme. Simulation results show significant improvements of our design on latency and power consumption.**

Keywords-Context Aware; MAC; TDMA; WBAN

I. INTRODUCTION

Wireless Body Area Network (WBAN) is an emerging wireless system that consists of body-worn sensors, implanted sensors, and control node. These nodes spread in a very small area with ultralow costs. One typical application of WBAN is for healthcare sector to continuously measure life parameters and thus detect life-endangering physical conditions. Sensor nodes for various functions (temperature, heart-rate, ECG, EEG) can generate data at a wide range of data rate from 10kb/s to 1Mb/s, which may result in a high potential for data overload and unacceptable latency. Besides, batteries of sensor nodes have limited ability due to their small size. Recharging or replacing the batteries is also very inconvenient. To solve the challenges on latency and energy, proper channel access and resource allocation mechanism is needed. Therefore, designing an efficient MAC protocol becomes very imperative.

In a ubiquitous medical monitoring environment, large quantities of data need to be collected. When contextual parameters such as the patient's activity or temperature of the environment suddenly change, the patient may suffer potential threaten to his/her life. During such emergency state, it is essential that data interested by health care providers can be transmitted in a real-time manner. Latency and throughput requirement for other data, however, can be loosened. For example, older people are likely to undergo a drop in blood pressure when suddenly sitting down or standing up. What usually happens next is that they feel faint but tend to ignore it. If this feeling continues and no diagnosis is given, older people may experience a blackout and ultimately a fall [1]. After old people sit down or stand up, medical staffs are interested in the variation of patients' blood pressure rather than other life parameters. Hence, timely transmission of data regarding blood pressure should be guaranteed and efficient delivery of other data is not absolutely necessary.

According to special designing requirement of WBAN and specific attributes of medical monitoring system, a context-aware MAC protocol is proposed in this paper. Specifically, the protocol is designed for a star-topology network which consists of a centrally controlled node called master node and several sensor nodes which collect data. Considering the architecture of network, a TDMA-based scheme is used because dedicated slot allocation naturally avoids collisions, idle listening, and overhearing of sensor nodes. This protocol has two states: normal and emergency. At most of time, sensor nodes work in a standard data rate and duty cycle to collect and transmit data to master node, which represents the normal state. Master node analyzes and processes data from one or several sensor nodes. If it detects abnormal status, there may be a particular danger to patients, such as a fall to older people. Then master node broadcasts reallocation information based on medical requirements of the particular danger and thus triggers the system into emergency state. As a result, sensor nodes increase or decrease data rate and duty cycle to adjust their sample rate and available bandwidth to meet requirements of the monitoring context. Therefore, medical staffs can monitor life-critical data in a timely way. In addition, on-demand slots allocation and sample rate configuration can make energy consumption more efficiently. This protocol also utilizes an optional synchronization scheme where sensor nodes would conduct resynchronization only if clock drift between master node and sensor nodes was so large that it causes slot overlapping. This approach decreases synchronization overhead existed in traditional TDMA protocols.

This paper makes contributions in these aspects. First, a new TDMA-based MAC frame structure is designed to implement context awareness and improve energy efficiency. Second, by applying context awareness, slot allocation is dynamically changeable depending on medical monitoring

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context. So sensor nodes with most interest to health care providers can sample more frequently and deliver more data if emergency state is triggered by the master node. Third, sensor nodes do not have to resynchronize in every MAC frame attributed to the optional synchronization scheme, which results in a reduction on overhead.

The rest of the paper is organized as follows. In section II, we briefly introduce related work. The design of the context-aware MAC protocol, including frame structure, context awareness, and optional synchronization, is presented in Section III. Simulation results and performance evaluation are given in Section IV. Finally we conclude this paper in Section V.

II. RELATED WORK

Most MAC schemes for wireless sensor network (WSN) can be categorized into two types: contention-based and TDMA-based. Contention-based MAC protocols have good scalability with no need to establish infrastructure. However, contention-based MAC protocols introduce much contention among sensor nodes. This usually leads to a high latency and power consumption, which are intolerable in WBAN for medical monitoring purpose. TDMA-based MAC protocols avoid collisions and reduce energy wastage by explicitly assigning specific time slots to sensor nodes and keeping sensor nodes asleep in other time. This kind of schemes is not easy to apply in network whose structure changes frequently. But due to fixed star topology and predetermined functions of sensor nodes, WBAN does not suffer from this problem. Furthermore, the necessity of synchronization deteriorates performance of TDMA network by introducing large overhead. However, using an optional synchronization with little energy wastage and complexity, TDMA-based scheme in this paper can be a good choice for medical WBAN.

For general WSN, existing MAC protocols are often designed for ad hoc WSN rather than star-topology WBAN. Typical WSN MAC protocols, such as S-MAC [2], T-MAC [3], and D-MAC [4], schedule a synchronized duty cycle between sensor nodes in order to reduce idle listening. But these schemes still suffer large power consumption due to synchronization overhead and periodical exchange of schedule messages. Moreover, they are not able to support management of emergency event for WBAN.

Recently, MAC protocols have been designed for WBAN by several researchers. Omeni *et al.* [5] propose a MAC protocol that adopts TDMA to avoid collision. The central node initiates communication by assigning one slot to each slave node. When an alarm is sent from one of slave nodes, the node can obtain extra slots for transmission. However, the alarm can be processed only when there is no scheduled slave node, which limits the protocol's ability to respond to emergency. Marinkovic *et al.* [6] also proposed a MAC protocol that using TDMA timing control to address energy problem. According to requests from sensor nodes, extra slots RSn are reserved for maintaining real-time transmission when errors occur. But constant slot assignment and inadaptability to emergency in this scheme can not fulfill the need of context awareness in WBAN. Plus, computation of resynchronization is done by sensor nodes, which increases overhead and complexity. A priority-guaranteed MAC protocol [7] is proposed to support contention-free high data rate communication. The control and data channel are both divided into two parts for consumer electronic application and medical application. Nodes compete and transmit data in their dedicated channels. This protocol has good performance in throughput and power consumption, but it has a complex superframe structure and fails to deal with emergency. O'Donovan *et al.* [8] proposed a context-aware BAN using FameComm MAC to ensure that different data can be transmitted under latency requirement. Nodes with high priority can interrupt those with low priority and utilize data aggregation to increase throughput. However, no evaluation of power consumption is given in [8]. Since this protocol is based on contention, it may incur serious collision with increasing network size. Besides, sensor nodes are usually designed to send data only. They lack the ability to decide when emergency state is and which type of data should be transmitted with high priority, which are complex computation process rather than simple out of bound measurement. Hence, the interrupt initiated by sensor nodes is impractical.

WBAN for medical monitoring requires that various types of data can be transmitted with acceptable latency in a most energy efficient and simple manner. MAC protocols mentioned above only consider part of requirements in medical WBAN whereas failing to consider other specific features. Hence, we need a context-aware MAC protocol to solve problems such as latency, power consumption, response to emergency, synchronization overhead, and practicality. In this paper, the idea of context awareness is extended and applied in a TDMA-based protocol. Because sensor nodes can obtain different number of slots depending on their priority and traffic loads, the problem of emergency and on-demand traffic can be solved by dynamically reallocating channel resources. Centrally controlled TDMA scheme and novel optional synchronization reduce the power consumption caused by contention and frequent resynchronization. Moreover, complexity of synchronization processing and emergency triggering is removed to master node, which makes this protocol easier to implement in reality.

Currently there is no standard proposed specifically for wireless body area network, but many WBAN applications using IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 (Zigbee) are developed in recent years [9]. IEEE 802.15.4 [10] is now the major low rate low power scheme for short-range wireless networks. IEEE 802.15.4e [11], which is an amendment of IEEE 802.15.4, is also going to be published for supporting industrial applications, such as industrial automation. Since the low-rate wireless personal area network is of most similarity to WBAN and the MAC frame structure in this paper borrows some ideas from that of IEEE 802.15.4 MAC, we compare the context-aware MAC protocol with IEEE 802.15.4 MAC in section IV.

III. MAC PROTOCOL DESIGN

A star network topology is adopted for MAC protocol in this paper. Sensor nodes which are heavily energy constrained periodically sample local life parameters, and send them to master node which acts as a central controller. Master node is

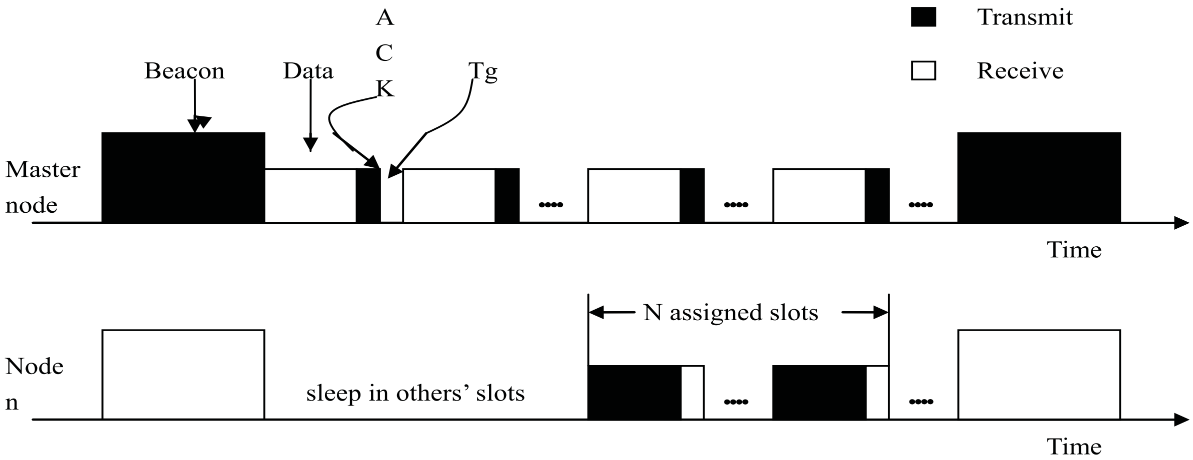

Figure 1. TDMA MAC frame structure.

usually a PDA or cell phone with more energy and better processing ability. It can relay data for long-distance transmission or complete advanced computation like life-endangering situations detection and optional resynchronization. It is assumed that the monitoring context is already known, which means network parameters including data rate and slot allocation is predetermined by the disease or health condition of specific patient.

A. TDMA-based MAC Frame Structure

According to the requirement of MAC protocol design for medical WBAN, a centrally controlled TDMA-based scheme can well address the problems of collision, idle listening and overhearing, because sensor nodes only transmit data in their dedicated slots. Sensor nodes periodically sleep and wake up and therefore mitigate power consumption. The TDMA-based MAC frame structure is given in Fig. 1 and consists of two parts: beacon and data transmission.

In *Beacon* slot, master node assigns slot for each sensor node by broadcasting a beacon packet. When establishing communication link, sensor nodes also synchronize themselves to master node through abstracted synchronization information in the first beacon packet. *Data* slots are assigned to sensor nodes for contention-free data transmission. Sensor nodes can obtain one or more slots for periodic or bursty application depending on their traffic characteristics. This on-demand slot allocation mitigates the frame overhead caused by fixed slot allocation where nodes with low transmission frequency hold reserved slots in every frame. Within a slot, a sensor node must wait for reception of an ACK packet from master node to acknowledge successful transmission of a data packet. There is also a guard time slot (*Tg*) between two *Data* slots in order to prevent slot overlapping. When data transmission in the last slot is finished, next frame begins with another *Beacon* slot. The length and slot allocation of next frame remains fixed if master detects no danger in the previous frame. Otherwise, the structure of next frame should be changed to meet the requirements in emergency state.

B. Context-Aware Design

Within a specific monitoring context, e.g., preventing falls for older people, data which are of most interest to health care providers should be transmitted under strict latency requirements. In this paper the proposed MAC protocol uses context awareness to satisfy this requirement. After all sensor nodes receive the first beacon packet, the system starts with normal state. Sensor nodes then send the sampled data to master node in their assigned slots respectively. As long as a sensor node completes its data transmission in assigned slots or there is no available date packet in the sensor's buffer, it must go to sleep to save energy. All sensor nodes wake up at the *Beacon* slot of a new frame, for the purpose of checking if there is a new beacon packet. If no beacon packet is sensed, sensor nodes return to sleep and will not wake up until their assigned slots are available. The structure of frame stays unchanged and this normal state of system will be periodically repeated if master node continuously chooses not to broadcast a new beacon packet. However, if a new beacon packet is received, it indicates that master node has detected abnormalities of the patient by data processing and analysis within the previous frame and hopes to trigger emergency state. Then all sensor nodes take the updated information about slot allocation and a new frame structure is formed. Those sensor nodes which are of most relevance to the monitoring context obtain higher duty cycle, which implies more slots for transmitting data. At the same time, these nodes also increase their sample rate to fulfill emergency monitoring task. Other unconcerned nodes, however, may mitigate available bandwidth and sample rate, or even cease data transmission, resulting in reduction of energy wastage. The emergency state lasts for a while until master node broadcasts another new beacon packet altering the system back to normal state.

C. Optional Synchronization

Overhead caused by frequent exchange of synchronization information is the main obstacle of traditional TDMA protocols. Trying to decrease the synchronization overhead, a novel optional synchronization scheme is proposed. A sensor node should encapsulate local clock information into a data packet. When master node receives the data packet, it takes the clock information and compares that with its local clock information. If the time interval between two clocks exceeds the guard time slot *Tg*, a parameter called clock offset is set as the interval. Otherwise, no operation occurs. Then master node then encapsulates clock offset into ACK packet and sends it to corresponding sensor node. The sensor node can adjust local clock relying on the value of clock offset after receiving ACK packet. By applying this scheme, sensor nodes only need to resynchronize when clock offset causes slot overlapping. They don't have to synchronize in every TDMA frame. In addition, all the computing tasks are distributed to master node which is less energy-constrained and thus sensor nodes simply need to passively extract and adjust clock information.

IV. MAC Protocol Evaluation

Compared with IEEE 802.15.4 MAC, we evaluate the context-aware MAC protocol in terms of end-to-end packet latency and energy efficiency.

A. IEEE 802.15.4

According to IEEE 802.15.4, there are two operation modes: beacon-enabled and nonbeacon-enabled. Beacon-enabled mode with ability of reliable MAC control is more suited to implement in WSN. This kind of network applies slotted CSMA/CA scheme where nodes compete for transmission opportunity in contention access period (CAP). Meanwhile, nodes may also compete to request guarantee time slot (GTS) which belongs to contention free period (CFP). In this scheme, a node firstly backs off a random interval between 0 to 2^{BE}, where BE stands for backoff exponent. Then it starts clear channel assessment (CCA), the duration of which is defined by contention window (CW). If the channel is found to be idle during CCA period, the node begins data transmission in the next slot. However, if the channel is busy, the node waits for another interval before attempting transmission again and increase both BE and the number of backoff times by one. This procedure will not stop until a successful transmission occurs or the number of backoff times reaches NB, the maximum number of backoff times. By applying IEEE 802.15.4 MAC, nodes have to at least conduct backoff once and CCA twice to obtain transmission chance, which introduces unacceptably long latency for WBAN. Power consumption problem also becomes serious with network size becoming large.

B. Simulation Configuration

Because no standard for physical layer of WBAN is developed, the channel model of IEEE 802.15.4 is utilized in the simulations. The wireless transceivers operate in 2.4 GHz band with data rate of 250kbps. The default values of current draw are specified according to MICAz mote [12].

The simulation model is a star topology with a master node and twenty sensor nodes. These sensor nodes are equally divided into four groups (A, B, C, D) which correspond to four kinds of data rate: 1.25kbps, 2.5kbps, 5kbps, and 10kbps. It is assumed that sensor nodes in group A and group B collect the most critical life parameters within this monitoring context. In other words, when master node triggers the system into emergency state, sensor nodes in group A and group B must adjust to a high data rate and duty cycle for real-time transmission of collected data. To testify different control manners for unrelated nodes, during emergency state group C are turned off and group D keep their original data rate and transmission slots. The simulation runs three times and each one lasts ten minutes. We assume master node detects abnormal condition at 180 seconds after simulation begins and the system stays in emergency state for 220 seconds. The network parameters of both normal and emergency state are given in Table I. When simulating IEEE 802.15.4 MAC, beacon-enabled mode with full GTS is used. According to monitoring context stated above, two nodes in group A and five nodes in group B are set to utilize GTS in order to support transmission of life-critical data by avoiding collision.

TABLE I
NETWORK PARAMETERS FOR PROPOSED CONTEXT-AWARE MAC

Network Parameters	Normal State	Emergency State
Sample Rate (Group A)	50Hz	200Hz
Sample Rate (Group B)	100Hz	200Hz
Sample Rate (Group C)	200Hz	0
Sample Rate (Group D)	400Hz	400Hz
Assigned Slots (Group A)	1	2
Assigned Slots (Group B)	2	2
Assigned Slots (Group C)	4	0
Assigned Slots (Group D)	8	4
Frame Length	100ms	54.36ms
Tg: Guard Time Slot	0.1ms	0.1ms
Slot Length	1.304ms	1.304ms
Packet Size (25 bits per sample)	125bits	125bits

C. Simulation Results

1) Latency: We calculate the time interval between the generation time of data packets at sensor nodes and the reception time of data packets at master node to signify end-to-end packet latency. Since WBAN is usually implemented in short range (e.g., less than 5 meters) and channel data rate is set to 250kbps, the relatively low propagation delay is ignored. We show the average end-to-end latency of all data packets as a function of time in Fig. 2. It can be seen from the figure that when proposed context-aware MAC protocol switches to emergency state the average latency diminishes to a low level. This is because the protocol reduces the length of TDMA frame by turning off sensor nodes in group C. As a consequence, sensor nodes that are still on can obtain subsequent transmission slots as soon as possible. The average latency goes back to a relatively high level at the time of 400 second when this protocol changes back to normal state. Nevertheless, in IEEE 802.15.4 MAC, sensor nodes in group A and group B still need to compete with other irrelevant nodes in CAP for available GTS allocation. This phenomenon introduces large latency, as shown in Fig. 2.

To verify the advantage of proposed protocol with higher traffic load, we increase sampling rate of group A in normal state to 66.7Hz and show the results in Fig. 3. Since generated packets cannot be transmitted in time within current frame when the network is saturated with traffic, the latency of both two systems in such scenario is larger than that with lower

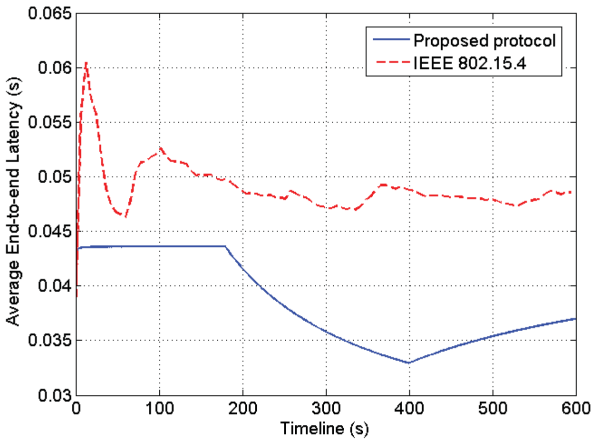

Figure 2. Average end-to-end latency of all data packets versus time using proposed MAC protocol and IEEE 802.15.4 MAC protocol.

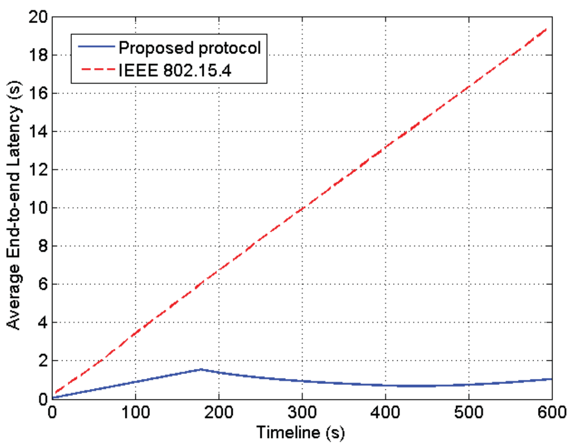

Figure 3. Average end-to-end latency of all data packets versus time using proposed MAC protocol and IEEE 802.15.4 MAC protocol with relatively high traffic loads.

traffic as in Fig. 2. The proposed MAC protocol greatly outperforms IEEE 802.15.4 MAC in latency. This is because the increased bandwidth in emergency state provides extra transmission opportunities for packets buffered in normal state. Thus average access delay of packets is reduced to some extent. However, when it comes to IEEE 802.15.4 MAC, data collisions caused by CSMA/CA become more serious with higher traffic load. Transmitting packets will experience larger access delay than previously transmitted packets, and consequently the latency of packets continuously increases.

Although proposed context-aware MAC protocol does not respond to emergency immediately, it still shows good performance in latency. Since sensor nodes periodically sense the beacon packet in every frame, the protocol only need to waits at most for one TDMA frame to enter into emergency state after master node detects abnormal condition. This mechanism shows low latency, but has a chance to incur large

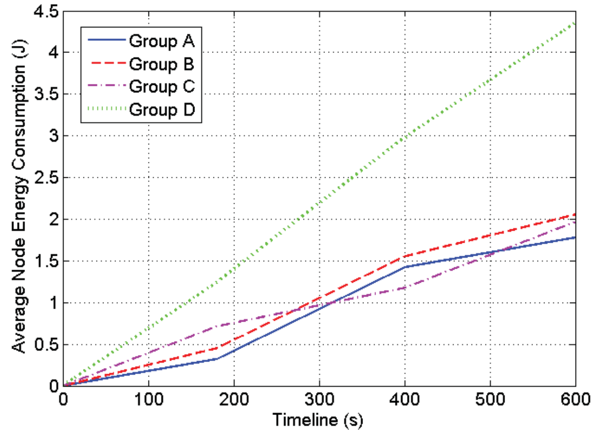

Figure 4. Average node energy consumption for Group A, Group B, Group C, and Group D, respectively.

power consumption which will be discussed in following subsection.

2) Energy Efficiency: When sensor nodes periodically sleep and wake up, power consumption primarily results from transmission, reception, idle listening, overhearing and sleeping. Other energy-consumed factors are ignored in this simulation model. To stress the contribution of energy savings made by context awareness, an average node energy consumption curve for each four groups is given in Fig. 4. As shown in the figure, Group A and group B have higher growth rate of energy consumption in emergency state than that in normal state. This is because these nodes obtain more traffic load and more transmission opportunity due to their increased data rate and transmission slots in emergency state. Although the number of assigned slots for group B stays in two, the shortened length of TDMA frame makes sensor nodes in group B obtain more transmission slots per time unit, compared with normal state. Plus, group A has a relatively low traffic load and transmission bandwidth in normal state compared with group B, which confirms that energy consumption curve of group A keeps a little below that of group B. Because of keeping their network parameters constant, group D shows a fixed energy growth rate and the highest energy consumption. Additionally, it can be inferred that group C cost energy slower in emergency state than normal state since they only sleep and sense the beacon packet in Beacon slot without any data transmission.

Power consumption is highly influenced by nodes activity. It is not fair to evaluate energy performance merely by comparing the absolute value of power consumption of two systems without specifying nodes' activities. For example, two systems with the same power consumption may differ greatly in their overall throughput. Therefore, the average node power consumption per kilo bits is used here to indicate energy performance. The bar chart in Fig. 5 shows comparison of two systems. Five parts of bar chart stand for overall system and A, B, C, D four groups respectively. Although IEEE 802.15.4 MAC adopts seven GTS to save energy, proposed context-aware MAC protocol still presents a superior performance.

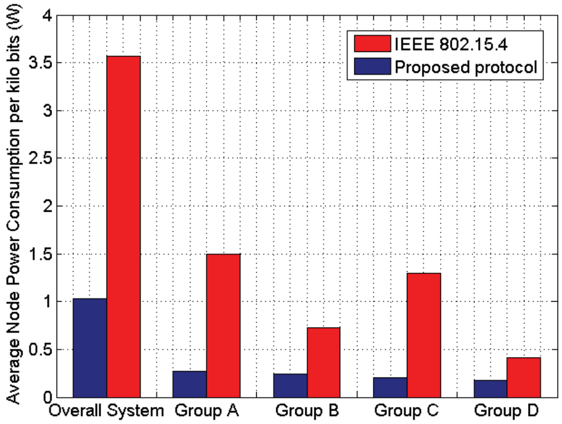

Figure 5. Bar chart comparing average node power consumption. Five parts stand for overall system, Group A, Group B, Group C, and Group D, respectively.

This is attributed to the fact that context awareness eliminates data transmission of unconcerned nodes as much as possible. In addition, the TDMA timing control and periodical sleeping and waking up scheme further reduce power consumption. Hence, compared with these energy savings, power consumption caused by frequent sensing of beacon packet stated before are well compensated. Using CSMA/CA, however, IEEE 802.15.4 MAC need to compete for the channel and therefore waste more energy.

V. CONCLUSIONS

A context aware strategy is adopted in the proposed MAC protocol. This ensures the real-time monitoring of important life parameters by dynamically changing data rate and duty cycle of sensor nodes. Proper variations of slot allocation also eliminate data transmission of unconcerned sensor nodes. The implementation of TDMA structure and optional synchronization further improve system-level performance. Simulation results show the context aware MAC protocol incurs lower end-to-end latency and power consumption when compared with IEEE 802.15.4 MAC.

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