An Energy-efficient MAC Protocol for Wireless Body Area Networks

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Abstract: A WBAN node may be working in two monitoring modes, all-transmit mode and few-transmit mode. Every mode has its own usage scenarios. To effectively prolong its lifetime, a node should be working in few-transmit mode as much as possible. An adaptive medium access control (MAC) protocol is specially designed to serve the nodes working in few-transmit mode. Experimental results show the proposed MAC protocol can improve the energy efficiency and satisfy the data delivery delay demands simultaneously.

1 Introduction

The resultant force from the advances of microelectronics, wireless communications, intelligent sensors and battery has given rise to the birth of wireless body area networks (WBANs). With many prominent advantages, WBANs are hopeful to launch a wave of medical, entertainment, gaming, sports and fitness applications [1].

A WBAN generally takes on a star structure which is comprised of one coordinator and some sensor nodes. A sensor node may be working in two monitoring modes. A node working in this first mode senses the physiological phenomenon with a certain frequency and reports all the measurements to the coordinator. In contrast, a node working in the second monitoring mode still needs to sense the target with a certain frequency, but the measurements are only conveyed to the coordinator on some occasions. In this paper, we name this two monitoring modes *all-transmit* mode and *few-transmit* mode.

Two monitoring modes have their own usages. The all-transmit mode can collect vast quantities of detailed information about one patient's body in a long period of time so that the medical staff can master the change-rules through analyzing these information. Compared to the all-transmit mode, the few-transmit mode only delivers data to the coordinator when some abnormal conditions are detected. As a result, it cannot provide enough detailed information for the medical staff to detailedly trace the patient's health in a long run, but it still can afford proactive wellness management, including early detection and prevention of diseases.

The traffic patterns generated by two monitoring modes are different. Generally speaking, nodes working in all-transmit monitoring mode produce busy periodic traffic which consumes a mass of communication resource. Transporting these vast quantities of data from the nodes to the coordinator means high cost of energy because communication dominates the energy consumption in such case [1]. In consequence, the lifetime of a node adopting this monitoring mode will be severely shortened. Compared to the all-transmit mode, the traffic generated by the few-transmit mode is rather sporadic and low. Hence, the prominent advantage of the few-transmit mode lies in the greatly reduced communication energy, which means much longer service time.

The few-transmit mode is particularly suitable for the healthcare of people with rather good or passable health conditions, e.g., the elderly and chronically ill people. For these people, it is unnecessary to adopt the all-transmit mode to closely monitor these people's health conditions. With the potential of saving more energy, the few-transmit mode is more appropriate for these applications. However, the normal operation and higher energy efficiency still cannot be obtained without the help of suitable MAC protocols [2, 3]. For a sensor node, radio is generally the part which consumes most energy. In order to extend the lifetime of a node from days to years, the only way is duty cycling the radio, that is, turning on its radio only when necessary and keeping it turned off otherwise, and this is just one task of the Medium Access Control (MAC) layer which drives the radio hardware [4].

In this paper, an adaptive medium access control (MAC) protocol is specially designed to serve the few-transmit nodes (thus it is called FT-MAC). With elaborate design, the superframe structure can support a WBAN in which the few-transmit nodes and the all-transmit nodes coexist. The rarity of traffic in the few-transmit mode is taken into account to improve the

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energy efficiency. Long superframe structure is adopted to cut down the overhead of transmitting and receiving beacon frames. Most of the superframe is assigned to be inactive period to reduce the duty cycle. Short insertion time slots are embedded into the inactive part of the superframe to meet the communication demands of the few-transmit nodes. Special mechanisms are designed to handle the transmissions of big frames and possible collisions caused by multiple nodes. Experimental results demonstrate the proposed MAC protocol can improve the energy efficiency and satisfy the data delivery delay demands simultaneously.

Section 2 introduces the superframe structure of the proposed MAC protocol. The performance of the proposed protocol is evaluated in Section 3. Finally, conclusions are drawn in Section 4.

2 Superframe of FT-MAC

Figure 1 (a) shows FT-MAC's basic superframe structure, which is used when all nodes are working in the few-transmit mode. The beginning of the superframe is a beacon frame which contains information such as timestamp, beacon interval, time slot length, time slots assignments, etc. Following the beacon frame, there may exist an optional broadcast period and a contention free period (CFP) which contains some guaranteed time slots (GTS). The optional broadcast period is used by the coordinator to broadcast long messages to all the nodes. One GTS slot in the optional CFP period can be used by the coordinator to transmit a long frame to one node, or can be used by one node to transmit a long frame to the coordinator.

Following the CFP period is a long inactive period which occupies most of the superframe. Because the traffic is very low when all nodes are working in the few-transmit mode, a long inactive period can help the coordinator and nodes to save energy. Short active insertion slots are inserted into the inactive period to deliver data. An insertion slot can be shared by all nodes to transmit data or network commands to the coordinator directly. Slotted Aloha is used by all nodes to share an insertion slot.

At the end of a superframe is an optional contention access period (CAP) which is used by all nodes with data to transmit the data using carrier sense multiple access with collision avoidance mechanism (CSMA/CA). The existence of this CAP period depends on if there are collisions happen or not during current superframe. If there are frames collided in one insertion slot, such a CAP period will be activated to retransmit these frames.

The superframe structure displayed in Figure 1 (a) cannot satisfy the demands of a WBAN in which there are nodes working in the all-transmit mode. The superframe structure shown in Figure 1 (b) is designed for such occasions. In Figure 1 (b), loop periods replace the place of the inactive period in Figure1 (a). One loop period begins with an active period that is used for the nodes working in the all-transmit mode to transmit their data. The active period can adopt complex structure to accommodate the nodes working in the all-transmit mode.

From Figure 1, it can be observed that one insertion slot can be composed of one DATA section and one ACK section. Multiple DATA sections can be included in an insertion slots to convey data for the coordinator and nodes working in the few-transmit mode. If the traffic in the WBAN is low, then only one DATA section is configured in one insertion slot. If one DATA section is not enough, then more DATA sections are used. For a WBAN of dozens of nodes, this mechanism can divide the nodes into several groups to alleviate collisions. To support communications of two directions, two types of insertion slots are designed. One is used for the coordinator to transmit data packets or commands to nodes, and the other one is used for nodes to transmit data packets or commands to the coordinator. We call the first type of insertion slots "download" insertion slots and the second type of insertion slots "upload" insertion slots.

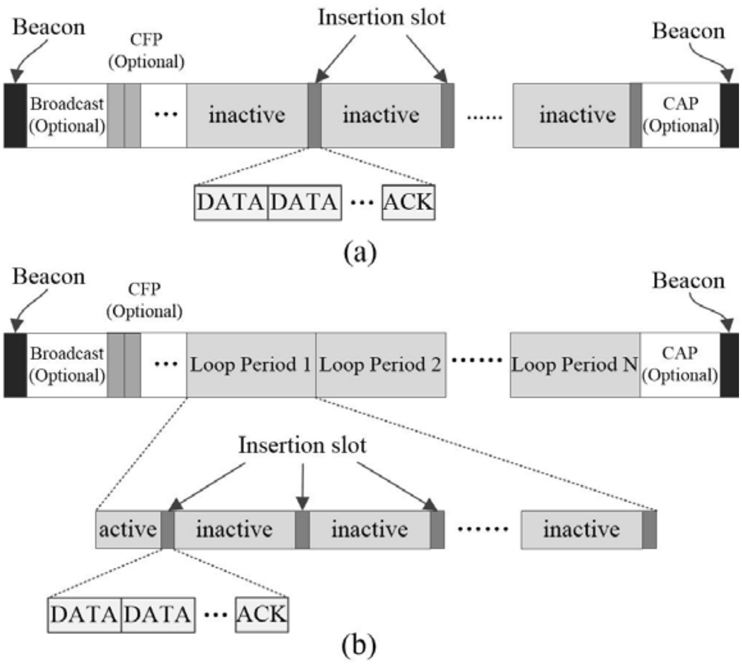

Figure 1. The superframe structure of FT-MAC

Because there is only one ACK section in one insertion slot, one download insertion slot only has one DATA section. This means the coordinator can only send data to one node and be acknowledged by that node. For an insertion slot, there can be multiple DATA sections, which are acknowledged by the coordinator using the same ACK section. Only unicasts are acknowledged, and broadcasts are not acknowledged.

The ACK section can also be used by the coordinator to send special “BREAK”, “CAP”, “SYNC” commands to all the nodes. The coordinator can also use download insertion slot to send these commands. A “BREAK” command means the current superframe will be broken, and a new superframe will start. If a node receives such a command, it waits for the end of ACK section and prepares to receive a new beacon. A “CAP” command signifies an additional CAP period. If a node receives such a command, it waits for the end of the ACK section, and then enters a CAP period. After the CAP period, all nodes prepare to receive a new beacon frame and start a new superframe. “SYNC” commands are adopted to transmit time synchronization information to all nodes. If a node receives such a command, it retrieves the synchronization data and uses it to synchronize its clock.

3 Performance Evaluation

Two star WBANs are used in the experiments. One WBAN has 5 nodes and another has 20 nodes. OMNeT++ [5] is adopted as the simulation tool. The parameters of the radio parts of all nodes and the coordinators are based on CC2520 [6]. The energy efficiency and data delivery delay of three MAC protocols, 802.15.4 [7], AB-MAC [8] and FT-MAC are compared. The beacon lengths of 802.15.4 and FT-MAC are assumed to be 30 and 34 bytes. The ACK frame length of 802.15.4 is 5 bytes. The DATA frame and ACK frame of FT-MAC are 10 bytes and 6 bytes. For FT-MAC, the number of insertion slots in a superframe is 4. For AB-MAC, the number of standby slots in a superframe is also set to be 4. The settings of 802.15.4 and AB-MAC are from [8] and [9].

We fix the beacon/standby/insertion intervals all to be 0.5s and examine the performance of three MAC protocols under different traffic. Both the WBAN of 5 nodes and the WBAN of 20 nodes are used here. For the WBAN of 20 nodes, two FT-MAC schemes are used. The first scheme sets only one DATA section in an insertion slot and the second sets two DATA sections in an insertion slot. 20 nodes are divided to 2 groups, and each group uses one DATA section. All nodes are configured to have a same data occurrence interval. 90% of the data are small data, and 10% of the data are big data. The average data interval changes from 1 to 10000 seconds.

Figure 2 and Figure 3 display how the average power consumed by a node change with the traffic. As the figures show, AB-MAC and FT-MAC cost less energy when the traffic is low. However, as the traffic becomes high, the energy consumptions of AB-MAC and FT-MAC increase more rapidly than 802.15.4. Beyond one point, the average power of AB-MAC and FT-MAC exceed 802.15.4. The speed of AB-MAC grows the fastest because the adaptive beacons grow fast and AB-MAC communicates twice to deliver a frame. FT-MAC only communicates once to deliver a small data, and it only has to communicate twice for a big data. By using two DATA sections, FT-MAC GN = 2 can reduce the collisions so that it can gain higher energy efficiency.

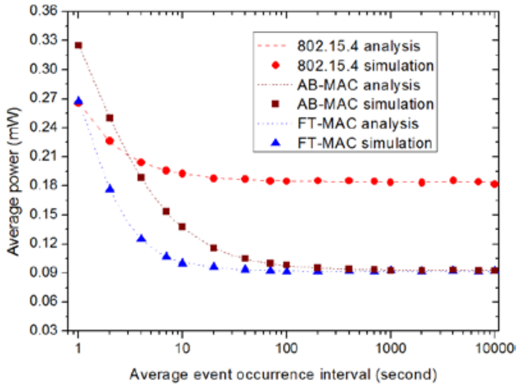

Figure 2. The effect of the average event occurrence interval on node average power (5 nodes)

Figure 4 and Figure 5 shows the effect of the average data occurrence interval on the average power consumed by the coordinator. As the traffic grows, the coordinator needs to increase its duty cycle to convey more traffic. Therefore, the average powers of all protocols increases with the traffic become high. As the traffic is low, both AB-MAC and FT-MAC cost less energy than 802.15.4. The average power of AB-MAC grows the fastest as the traffic becomes dense. The reason lies in the beacon frames and access slots brought by the increasing traffic. FT-MAC and FT-MAC GN = 2 grow slower than AB-MAC, yet they both grown faster than 802.15.4. The reason to explain this lies in the CAP periods and beacon frames caused by collisions. FT-MAC GN = 2 spends less energy than FT-MAC because it can alleviate collisions effectively.

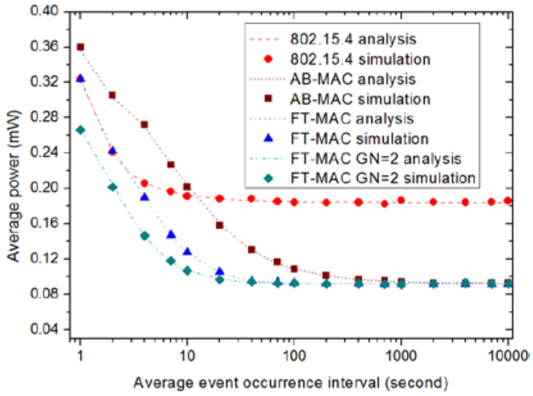

Figure 3. The effect of the average event occurrence interval on node average power (20 nodes)

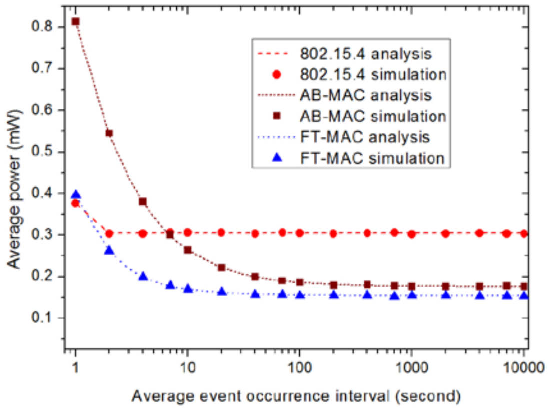

Figure 4. The effect of the average event occurrence interval on coordinator average power (5 nodes)

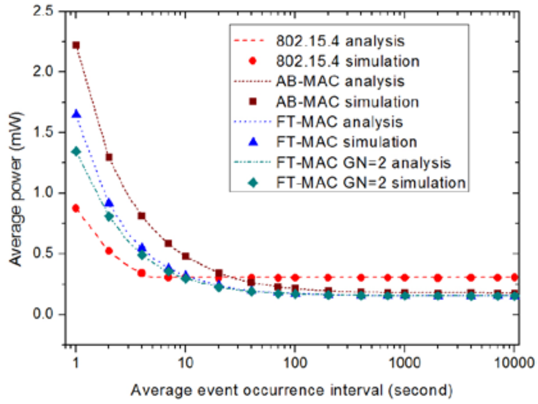

Figure 5. The effect of the average event occurrence interval on coordinator average power (20 nodes)

Finally we examine how the average frame delay changes with traffic. The average frame delays of three MAC protocols are shown by Figure 6 and Figure 7. For 802.15.4, the average frame delay remains almost constant for the WBAN of 5 nodes, and the average frame delay only increases a little as the traffic grows high for the WBAN of 20 nodes. The delays of AB-MAC and FT-MAC are a little higher than 802.15.4 because the frames have to wait longer time, and their delays exhibit obvious rise as the traffic becomes busy. This can also be explained by the beacon frames and other periods introduced by busy traffic.

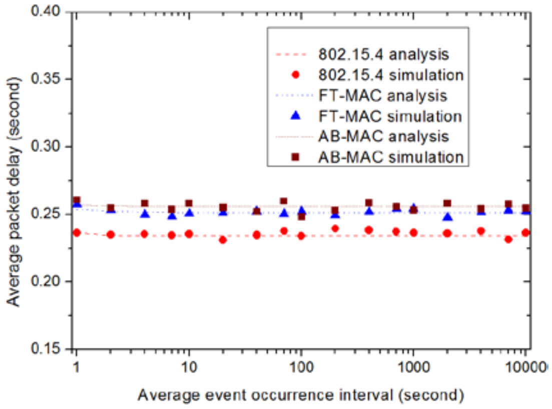

Figure 6. The effect of the average event occurrence interval on average frame delay (5 nodes)

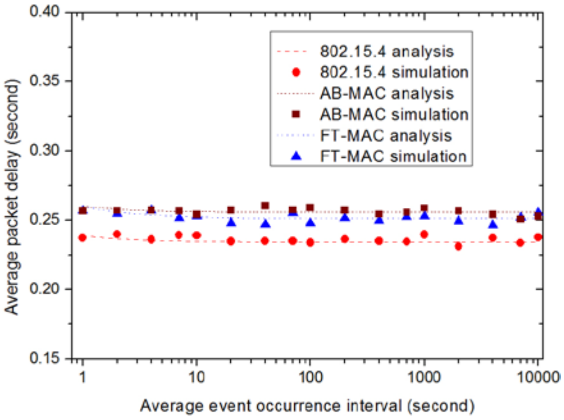

Figure 7. The effect of the average event occurrence interval on average frame delay (20 nodes)

5 Conclusion

In this paper, we analyze the tasks and two working modes of WBAN nodes. To extend the lifetime, a node should try to work in few-transmit mode as much as possible. Focusing on the requirements of the nodes working in few-transmit mode, a beacon-enabled adaptive MAC protocol (FT-MAC) is proposed. FT-MAC adopts long superframes to reduce the overhead of beacon frames to save energy. Short insertion time slots embedded in the inactive period are used to provide opportunities for few-transmit nodes to transmit their data. Insertion time slots can be viewed as a combination of the beacon frames and CAP periods used in traditional MAC protocols. Different transmission mechanisms are designed for small data and big data. By adopting a flexible structure, FT-MAC can support a WBAN in which few-transmit nodes and all-transmit nodes coexist. For a WBAN of dozens of nodes, multiple DATA sections can be used as a makeshift to alleviate the collisions if the traffic is not busy. However, as the traffic become busy, beacon frames and other periods caused by frequent collisions result in severe performance degradation. As a result, FT-MAC is not applicable for WBAN applications with high traffic.

Acknowledgment

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