Power-Efficient Packet Scheduling Method for IEEE 802.15.3 WPAN*

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Abstract. Power efficiency is the key issue for mobile devices, which mainly rely on limited battery power. The IEEE 802.15.3 wireless personal area network (WPAN) standard adopts a time division multiple access (TDMA) protocol controlled by a central device to support isochronous traffics. In the TDMA-based wireless packet networks, the packet scheduling algorithm plays a key role in power efficiency. However, the standard suffers from long access delay and association delay which increase the power consumption. In this paper, we propose a packet scheduling method to improve the power efficiency. Performance evaluations are carried out through simulations and significant performance enhancements are observed. Furthermore, the performance of the proposed scheme remains stable regardless of the variable system parameters such as the number of devices and superframe size.

1 Introduction

The IEEE 802.15.3 task group (TG) has been chartered to create a high-rate WPAN (HR-WPAN) standard and has published a final standard [1]. The IEEE 802.15.3 provides short range wireless connectivities among consumer electronics and portable devices. HR-WPAN adopts a time division multiple access (TDMA)-based medium access control (MAC) protocol. In HR-WPAN, a pair of devices (DEVs) can communicate through peer-to-peer connectivity without contention during an allocated time slot called *channel time*. The data packet can be transmitted during the channel time and the allocation of channel time for each DEVs is controlled by a scheduler in a piconet coordinator (PNC). Thus, the packet scheduling algorithm in the IEEE 802.15.3 standard is expected to play an essential role in the system performance. However, the standard does not define how to assign the channel time and leaves this for vendors.

Some efforts to define the packet scheduling method for the HR-WPAN have been made since the standard is published. Performance enhancement achieved by informing queue-status to a PNC using MAC header of every packet is proposed in [2]. This scheme adopts a flexible superframe size to handle variable bit

* This research was supported by the Yeungnam University research grants in 2005.

L.T. Yang et al. (Eds.): ICESS 2005, LNCS 3820, pp. 462–472, 2005.

rate (VBR) traffics. The piggybacked information may be useful when there is a burst transmission. However, the channel time allocation algorithm for different traffic types is not considered. An algorithm proposed in [3] focuses on utilizing wasted or remained channel times. The authors in [4] propose a channel time allocation scheme for a specific application, MPEG 4 traffic. Since packets generated from an MPEG 4 encoder are classified into three types and are arranged by a periodic pattern, a central device can allocate channel time for transmissions of MPEG 4 packets according to the packet pattern. A packet transmission method without a preamble is introduced in [5] to reduce the preamble overhead in a high transmission rate. A scheduling method based on the queueing model is proposed in [6] to reduce the average waiting time.

Power management is an important issue for the battery-powered portable DEVs and its objective is to assist the DEVs to sleep and reduce the wakeup time as much as possible. There has been several work on the MAC design for power management in wireless system. However, most of them are based on the MAC of IEEE 802.11 WLAN [7]–[9] or IEEE 802.15.4 low-rate WPAN [10][11]. There is little work to address the power efficiency in HR-WPAN [12][13]. In [12], a power management method for intra-superframe is proposed for HR-WPAN. The proposed algorithm finds the suboptimal order to reduce the wakeup time by using graph theory. However, the inter-superframe power management problem and the VBR traffics are not considered in [12]. The authors in [13] utilize the network topology and UWB physical layer information to minimize the energy consumption per bit. This method increases the overhead since it requires power information, position information, and relay DEVs for its operation.

As far as we know, there is no work to minimize the power consumption in HR-WPAN combined with the packet scheduling method supporting constant bit rate (CBR) and VBR traffics. In this paper, we propose a packet scheduling method for HR-WPAN to efficiently reduce the power consumption. The proposed scheduling concepts apply to wireless packet systems in general. In the next section, MAC protocol in the IEEE 802.15.3 standard is briefly described. The proposed scheduling method for HR-WPAN is introduced in Section 3. Section 4 describes the simulation environment and evaluates the simulation results. Finally, the paper is concluded in Section 5.

2 IEEE 802.15.3 (HIGH-RATE WPAN)

2.1 MAC Protocol

In the HR-WPAN standard specifications, DEVs are communicating on a centralized and connection-oriented ad-hoc network called piconet. One of the participating DEVs must be designated as a piconet coordinator (PNC). The PNC provides basic timing information for the operation of the piconet and manages the QoS for delay sensitive applications.

The MAC layer in the IEEE 802.15.3 standard employs a time-slotted superframe structure. Fig. 1 illustrates the superframe structure in the HR-WPAN standard. The superframe consists of three major parts: a beacon, an optional

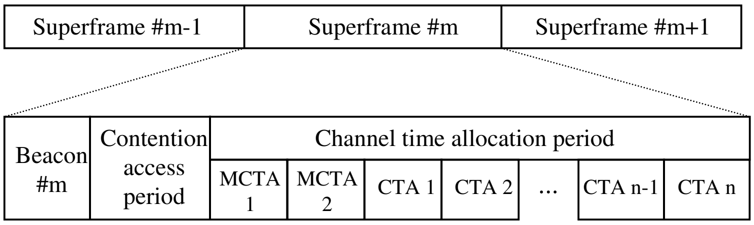

Fig. 1. Superframe structure of IEEE 802.15.3

contention access period (CAP) and a channel time allocation period (CTAP). The beacon packet is transmitted by the PNC at the beginning of each superframe. It allows all DEVs in a piconet to know about the specific information for controlling a piconet. The CAP is used for transmissions of short and non-QoS data packets and command/response packets. The remained period in the superframe is the CTAP. The CTAP is composed of management channel time allocation (MCTA) and channel time allocation (CTA) periods. The MCTA is used for sending command packets like CAP using the slotted ALOHA mechanism.

When a DEV needs a CTA on a regular basis, it sends a *channel time request* (CTRq) command to the PNC during the CAP or MCTA. Thus the PNC decides the durations of the superframe, CAP, and CTAP based on the DEVs requests. During a CTA period, a DEV can transmit several packets to a target DEV without collision. Each packet transmission may be followed by an acknowledgement (ACK) packet. The specification for the MAC protocol defines three acknowledgement types: no-acknowledgement (No-ACK), immediate-acknowledgement (Imm-ACK), and delayed-acknowledgement (Dly-ACK). For Imm-ACK, the receiver issues an ACK packet to the transmitter on every received packet. No-ACK means no ACK packet is issued. In Dly-ACK, which is a tradeoff between these two methods, the receiver issues an ACK packet for multiple received packets.

2.2 Association Process

In order to participate in a piconet, a DEV needs to join the piconet using the association process. Associating with the piconet provides the DEV with a unique identifier, the DEVID, for that piconet. When a DEV wants to leave the piconet or if the PNC wants to remove a DEV from the piconet, the disassociation process is used.

Before a DEV has completed the association process, all frames sent to the PNC by the DEV shall be exchanged either in the CAP of the superframe or in an association MCTA. An unassociated DEV initiates the association process by sending an Association Request command to the PNC. When the PNC receives an Association Request command, it shall send an Association Response command, indicating that the DEV has been associated. The PNC starts the association timeout period (ATP) timer once it has sent the Association Response command for the new DEV. The associating DEV needs to send the

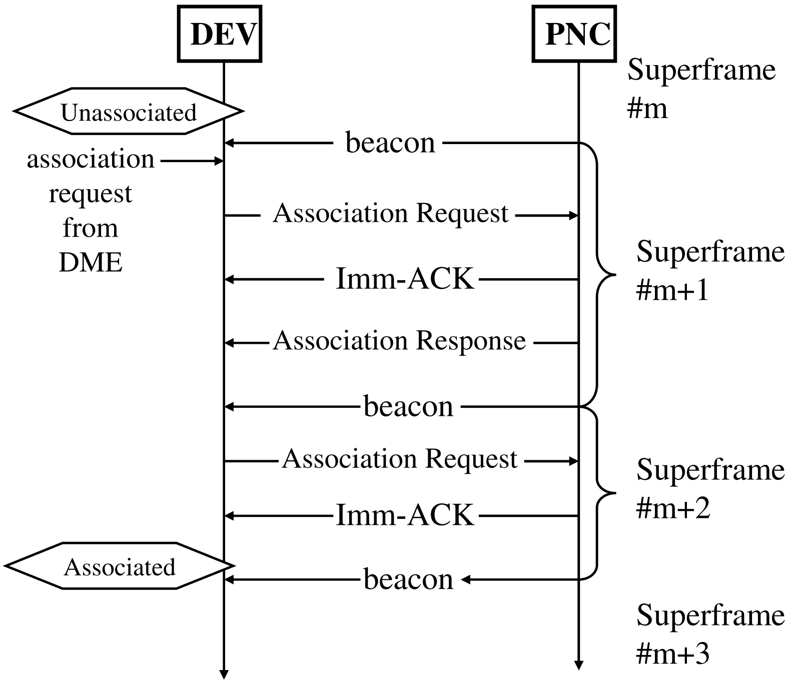

Fig. 2. An example of association delay

second Association Request command before the ATP timer expires. If the PNC receives the second association request command after the ATP timer expires, the PNC shall send the Disassociation Request command to the DEV requesting association to indicate that it has failed the association process. Fig. 2 illustrates the message flow for a successful association process. The association process is initiated by a device management entity (DME). Note that the completion of the association process may be delayed for more than two superframes when the CAP or the MCTA is not available at appropriate time instant in superframes $m + 1$ and $m + 2$.

2.3 Power Management

An important goal of the 802.15.3 standard is to enable long operation time for battery-powered DEVs. The best method for extending the battery life is to enable DEVs to turn off completely or reduce power for long periods of time. This standard provides three techniques to enable DEVs to turn off for one or more superframes: device synchronized power save (DSPS) mode, piconet-synchronized power save (PSPS) mode, and asynchronous power save (APS) mode. In any given power management mode, a DEV may be in one of two power states, either AWAKE or SLEEP states. AWAKE state is defined as the state of the DEV where it is either transmitting or receiving. SLEEP state is defined as the state in which the DEV is neither transmitting nor receiving.

PSPS mode allows DEVs to sleep at intervals defined by the PNC. A DEV in PSPS mode shall listen to all system wake beacon, as announced by PNC and is required to be in the AWAKE state during system wake superframes. DSPS mode is designed to enable groups of DEVs to sleep for multiple superframes. DEVs synchronize their sleep patterns by joining a DSPS set which specifies the interval between wake periods for the DEVs and the next time the DEVs will be awake.

The problem of PSPS and DSPS modes is that they are not efficient for multimedia traffics which have non-periodic inter-arrival time. APS mode is appropriate for these non-periodic traffics. The only responsibility of a DEV in APS mode is to communicate with the PNC before the end of its ATP in order to preserve its membership in the piconet. However, when the required sleep time is much longer than ATP, this method increases the overhead to maintain the membership and results in increased power consumption. Besides power consumption, the use of power management in the standard makes it difficult for the PNC to determine the interval for sleep period because of burst traffic arrivals.

3 Proposed Packet Scheduling Method

3.1 Motivation

Due to the TDMA property of IEEE 802.15.3 MAC, one of the key issues for power consumption is to schedule the order of the multiple CTAs among multiple DEVs to minimize the total wakeup times. The time duration from the packet arrival at the MAC layer to the transmission of the packet is called *access delay*. Fig. 3 shows an example of access delay caused by the lack of information about the actual packet arrival instant. Since the information given by a CTRq command does not inform the optimal time instant of a CTA, the packet arrival and

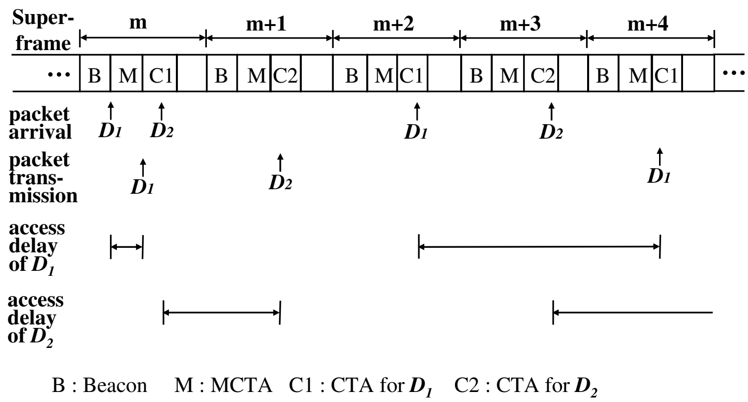

Fig. 3. An example of access delay

the CTA are not synchronized. The information delivered by a CTRq command is insufficient for the PNC to decide the duration and the location of a CTA for the requesting DEV. Thus, the average access delay increases as the packet inter-arrival time increases and may maintain until the end of the flow. Furthermore, it can be longer in heavy load cases since several CTAs overlap. Nevertheless, the packet scheduling method that considers the power consumption is not proposed in the standard and previous literatures.

The power management methods presented in the standard can not cope with the fast traffic changes and may cause incorrect system parameters which leads to the performance degradation. Moreover, these power management methods are futile for traffics which have long packet inter-arrival time. The IEEE 802.15.3 TG considers the scenario that DEVs frequently join and leave a piconet as mentioned in [14]. In this scenario, many system parameters such as a superframe length and the number of flows change dynamically. Thus, instead of using the power management method of the standard, we propose that a DEV leaves a piconet when it is neither transmitting nor receiving. This method is easy to be implemented and can reduce the overhead caused by the power management. In addition, we propose the packet scheduling method to reduce the wakeup time caused by the access delay and the association delay.

3.2 Packet Scheduling Method

A timer τ, which indicates the remained time until the CTA allocation, is used for the packet scheduling. The PNC selects DEVs whose values of τ are less than the time duration of a superframe, D_s. The selected DEVs are called a *candidate set*. DEV n in the candidate set is allocated Φ_n CTAs in the current superframe and Φ_n is given as

$$\Phi_n = \left\lceil \frac{D_s - \tau_n}{\alpha_n} \right\rceil, \tag{1}$$

where $\lceil x \rceil$ is the smallest integer value not less than x, α is an average packet inter-arrival time, and the subscript n in the notation denotes the nth DEV. For the candidate set, the time duration from the beginning of current superframe to the beginning of the cth CTA is given as

$$T_n^c = \tau_n + (c-1) \times \alpha_n, \quad \text{for} \quad 1 \le c \le \Phi_n. \tag{2}$$

During the MCTA, a DEV sends the status information to the PNC by using a *status report command* packet. We denote the values of queue size, access delay, and transmission rate in the status report command packet as F_n^Q, F_n^D, and F_n^R, respectively. Then the packet transmission time γ is given as

$$\gamma_n = \left(\frac{P_n}{F_n^R} + D_{\text{overhead}} \right) F_n^Q + D_{\text{guard}}, \tag{3}$$

where P is the packet size and D_{overhead} and D_{guard} are the time durations for the overhead and guard time, respectively. Thus, the scheduler assigns a CTA at T_n^c with γ_n duration for DEV n. When two or more scheduled CTAs overlap with each other, the CTA with lower value of T_n^c is allocated in advance.

The MCTA allocation method is proposed as follows. If there is time duration remained between two consecutive CTAs, this duration becomes MCTA for transmitting command packets. However, if the remained duration is less than the threshold, it is merged to previous or next CTA. The threshold is a sum of the slot time and the time duration of a CTRq packet. This threshold ensures that at least one command packet can be transmitted in an MCTA. The sum of CTAs and MCTAs durations allocated in a superframe should be less than D_s. If the duration sum is more than D_s, the CTAs at the tail will be removed until it becomes less than D_s.

Note that T_n^c and Φ_n are required (ideal) values for CTA allocations. Because of the aforementioned reasons of CTA overlap and dynamic traffic pattern, it may happen that the packet scheduler uses smaller values than T_n^c and Φ_n. In this case, the selected (real) values instead of T_n^c and Φ_n are denoted by t_n^c and ϕ_n, respectively.

At the start of a new superframe, τ_n is updated to a new value by

$$\tau_n \Leftarrow \begin{cases} \max\{0, \tau_n - D_s - F_n^D\} & , \text{ for } \tau_n \geq D_s, \Phi_n = 0 \\ \max\{0, \alpha_n - (D_s - t_n^{\Phi_n}) - F_n^D\}, & \text{for } \tau_n < D_s, \Phi_n = \phi_n > 0 \\ 0 & , \text{ otherwise.} \end{cases} \quad (4)$$

The first equation represents a DEV whose CTA is not allocated in the current superframe and the corresponding τ_n is subtracted by D_s and F_n^D in the next superframe. The F_n^D is an adjusting factor used to synchronize time instants between the CTA and the packet arrival. The second equation shows a DEV who belongs to the candidate set and transmits packets as required. In the third equation, when a DEV in the candidate set does not transmit packets as required, it gains higher priority in the next superframe.

In our proposed scheme, the transmission of status report commands plays an important role in allocating CTAs in a superframe. However, the PNC may form a superframe without any MCTA due to a heavy traffic load or an insufficient superframe size. To ensure that at least one status report command can be transmitted in a superframe, the PNC allocates at least one MCTA with the minimum MCTA time duration. Moreover, the last channel time in a superframe must be an MCTA, called essential MCTA (E-MCTA). This allows the latest status information of each DEV to be delivered to the PNC and to be reflected in the next superframe. The beacon packet in a superframe has information fields for the locations and durations of all CTAs as described in the IEEE 802.15.3 standard. Thus, the proposed scheme can be implemented with the operational compatibility to the standard.

The association delay is also expected to be reduced by using the proposed method. In the HR-WPAN standard, the DEV whose association request arrives during the CTA period should wait until the MCTA of the next superframe. On the contrary, in the proposed method, there are multiple MCTAs and E-MCTA in a superframe and the DEVs can send the association request packet at the next available MCTA in the same superframe. The disassociation request packet should also be transmitted during the MCTA and the proposed method may have less disassociation delay than that for the HR-WPAN standard. Because the DEV turns off the power after the completion of the disassociation process, the proposed method can reduce more power consumption.

4 Numerical Results

4.1 Simulation Environment

We assume that all DEVs except the PNC are uniformly distributed in the coverage area of a piconet with diameter 20 meters. The PNC is located at the center of the area. We consider one piconet in this simulation. The parameters used in this simulation are based on the IEEE 802.15.3 standards [1].

We study two real-time traffic types, CBR and VBR in the simulation. The CBR traffic flow is generated at 912 kbps [15]. For the VBR traffic model, actual MPRG-4 video streams of "Silence of the Lambs" with a mean bit rate of 580 Kbps and a peak rate of 4.4 Mbps, are used [16]. The packet sizes for both traffics are 2048 octets defined in the IEEE 802.15.3 standard. For the simulation of the association process, the intervals of the association and the disassociation requests are exponentially distributed with mean value of two seconds. In this simulation, CAP allocation is not considered since it is optional in the standard [1].

The scheme proposed in this paper, namely enhanced WPAN (EWPAN), is compared with the WPAN proposed in [2]. Each scenario is simulated for 10 minutes. We use the log-normal shadowing channel model [17]. We set the path loss exponent to 3.3 according to the SG3a alternate PHY selection criteria in [18] and the standard deviation to 7.67 [17]. The transmit power and antenna gain are set to 0 dBm and 0 dBi, respectively [18]. The received SNR is varied by the Ricean fading gain, which is generated according to the modified Clarke and Gans fading model [19]. For the data rate of the physical layer of each communication link, we assume that the system adapts the data rate by properly choosing one from a set of modulation schemes according to the channel condition as described in [20].

4.2 Simulation Results

The simulation results of the power efficiency, i.e. the number of transmitted packets divided by wakeup time are shown in Fig. 4 where the superframe durations (SF) are set to 65 ms, 45 ms, and 25 ms. The power efficiency of the proposed method (EWPAN) is better than that of the WPAN standard. This is because the access delay and the association delay of the proposed method is less than those of the WPAN standard. Note that the system parameters such as the duration of the superframe and the number of nodes have less effect on the performance of the proposed method compared with the WPAN standard. When the number of devices is 22, the power efficiency of the WPAN for the 25ms superframe duration is much lower than other cases because there is not enough MCTAs in a superframe.

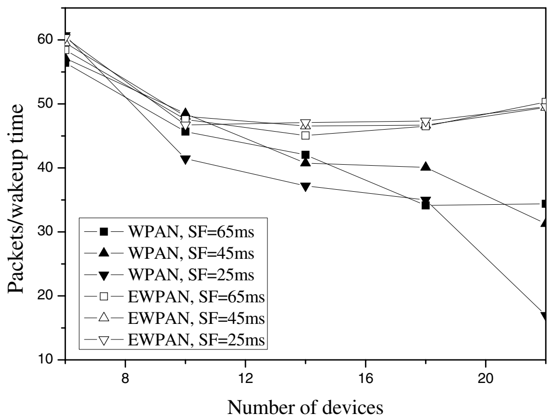

Fig. 4. Power efficiency for WPAN and EWPAN

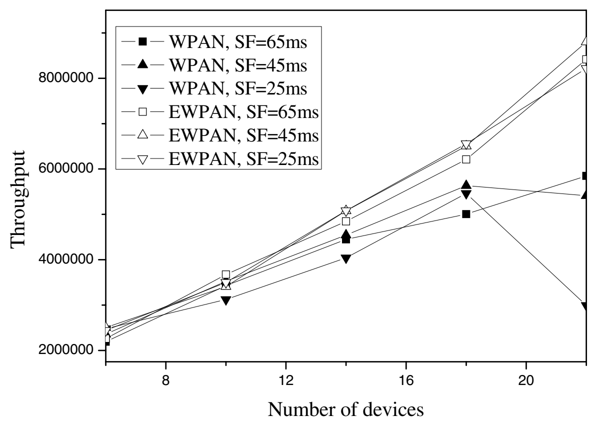

Fig. 5. Throughput for WPAN and EWPAN

The simulation results of the throughput are shown in Fig. 5. The proposed method has consistent performance while the WPAN has different performance depending on the system parameters such as the number of devices and the superframe duration. In WPAN, when the number of DEVs increases or the superframe duration decreases, the throughput decreases because the access delay and the association delay increases. The more important thing is that the proposed method shows better throughput than that of WPAN.

5 Conclusion

The access delay and the association delay of the HR-WPAN standard depend on the superframe duration or the packet inter-arrival time. Thus, the power consumption is restricted by the system parameters. In this paper, we propose an enhanced packet scheduling algorithm for the HR-WPAN to alleviate these design restrictions. The proposed scheme targets on battery-powered portable DEVs in HR-WPAN. The proposed algorithm synchronizes CTA to the packet arrival time and allocates sufficient time duration for the transmissions of pending packets.

We verify the performance enhancement by the simulation. From the simulations, we have shown that the proposed scheme gives significant performance improvements. We note that the performance of the proposed scheme is less influenced by the variable factors such as the superframe size and the number of flows. As a result, the proposed method shows less power consumption and more throughput than those of the HR-WPAN standard.

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