Adaptive Cross-Layer Packet Scheduling Method for Multimedia Services in Wireless Personal Area Networks

Sung Won Kim and Byung-Seo Kim

Abstract: **High-rate wireless personal area network (HR-WPAN) has been standardized by the IEEE 802.15.3 task group (TG). To support multimedia services, the IEEE 802.15.3 TG adopts a time-slotted medium access control (MAC) protocol controlled by a central device. In the time division multiple access (TDMA)-based wireless packet networks, the packet scheduling algorithm plays a key role in quality of service (QoS) provisioning for multimedia services. In this paper, we propose an adaptive cross-layer packet scheduling method for the TDMA-based HR-WPAN. Physical channel conditions, MAC protocol, link layer status, random traffic arrival, and QoS requirement are taken into consideration by the proposed packet scheduling method. Performance evaluations are carried out through extensive 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 (DEVs) and delay bound.**

Index Terms: **Cross-layer, IEEE 802.15.3, scheduling, wireless personal area network (WPAN).**

I. INTRODUCTION

Emerging wireless applications have been requiring communication networks not only to support both real-time and non-real-time services, but also to guarantee various quality of service (QoS) requirements. To meet the requirements over the wireless environment, tremendous efforts in each protocol layer have been made and performance improvements are achieved only in a specific layer.

Currently, there has been a shift in the design of recent generation wireless networks to support the multimedia services [1]–[3], so-called cross-layer design. That is, instead of isolating one layer from the others, several layers cooperate with each other in order to achieve synergetic effects in network performances. One of the areas using the cross-layer design is scheduling algorithm for packet transmission. The cross-layer packet scheduling method is based on not only the channel conditions and power limitation observed in the physical layer, but also the queue status, packet arrival, QoS requirements, and service discipline observed at the data link layer. The objective is to achieve a cross-layer optimization, which maximizes capacity and user satisfaction.

Wireless personal area networks (WPANs) provide short range (5∼50 meters) wireless connectivities among consumer electronics and communication devices. 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 [4]. To support higher data rates and better QoS, the HR-WPAN adopts a time division multiple access (TDMA)-based medium access control (MAC) protocol. In the HR-WPAN, a pair of devices (DEVs) can communicate through peer-to-peer connectivity without contention during an allocated time slot which is 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 QoS provisioning for multimedia traffic.

However, the packet scheduling method of a PNC is out of the scope of the IEEE 802.15.3 standard. Moreover, significant efforts for improving the packet scheduling method have not been made since the standard was published. Performance enhancements by informing queue-status (Q-status) of each node to a PNC are shown in [5] and [6]. In this scheme, the number of pending packets at each DEV are included in the MAC header of every packet. Thus, by overhearing every packet exchange, a PNC can allocate appropriate channel time for transmitting packets stored at a DEV in the next superframe. This scheme aims at handling variable bit rate (VBR) traffic and adopts a flexible superframe size. One potential drawback is that the size of superframe may change too frequently. This may introduce some difficulties in accurate timing and positioning for strictly time-bounded applications. Furthermore, the piggybacked information can be useful only when there is a burst to transmit. Moreover, the channel time allocation algorithm for different traffic types is not considered.

In [7] and [8], the authors designed a hierarchical superframe formation algorithm, which combines the advantages of both the static and dynamic algorithms to obtain a system with high performance and a broad scale of services. For the hierarchical superframe formation, mini-superframe is introduced and it can be allocated during the free slots and the wasted time slots. However, if the slot wastage occurs frequently, the mini-superframe allocations will also be performed frequently and the system performance will be decreased accordingly. Moreover, this scheme does not consider how to allocate the channel times. The authors in [9] propose a channel time allocation scheme for a specific application, MPEG 4 traffic. Packets generated from a MPEG 4 encoder are classified into three types and are arranged by a periodic pattern. Thus, 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 [10] to reduce the preamble overhead in a

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S. W. Kim is with the School of Electrical Engineering and Computer Science, Yeungnam University, Gyeongsangbuk-do, 712-749, Korea, email: ksw@ieee.org.

B.-S. Kim is with the Motorola Inc., 1301 Algonquin Rd. Schaumburg, IL, 60196 USA, email: Byungseo.Kim@motorola.com.

high transmission rate. A rate-adaptive MAC protocol for HR-WPAN is proposed in [11]. Based on the information from the physical layer, the receiver chooses an appropriate data rate and sends it back to the transmitter. The target application in [11] is asynchronous bursty data transmission requiring an acknowledgement packet. This method is not applicable to real-time services which do not require an acknowledgement packet.

In this paper, we propose an adaptive cross-layer packet scheduling method for the HR-WPAN to efficiently support the QoS requirements of multimedia services and to increase the system utilization. Physical layer conditions, link layer status, and MAC protocol cooperate with each other to support the proposed adaptive cross-layer packet scheduler. The proposed scheduling concepts apply to wireless packet systems in general.

In the next section, the MAC protocol in the IEEE 802.15.3 standard is briefly described. In addition, the way to support multi-rates defined in the standard is illustrated in the same section. The proposed scheduling method for the HR-WPAN is introduced in Section III. In Section IV, the performance analysis of the proposed method is evaluated. Section V describes the simulation environment and evaluates the simulation results. Finally, the paper is concluded in Section VI.

II. IEEE 802.15.3 (HIGH-RATE WPAN)

A. MAC Protocol

IEEE 802.15.3 HR-WPAN is a wireless ad hoc network called piconet that is distinguished from other types of networks by its short-range. All components in the piconet are DEVs and one of them is required to perform the role of the PNC. The PNC is a master device, which centrally controls the whole piconet. The PNC, using beacon frames, provides the basic timing and allocates channel times to each DEV. DEVs in a piconet can leave and join by using the association (call-connection) process. We define the association delay as the time duration between the arrival of the first packet and the transmission of the first packet during the association process.

Fig. 1 illustrates the superframe structure in the HR-WPAN standard. The superframe consists of a beacon frame transmitted by the PNC, an optional contention access period (CAP), and a channel time allocation period (CTAP). The CAP period is provided for commands or non-stream data transmissions, which ensures a light traffic load. In the CAP, DEVs use carrier sense multiple access/collision avoidance (CSMA/CA) for the medium access. The CTAP adopts a TDMA mechanism and allocates channel time allocation (CTA) period and management channel time allocation (MCTA) period. The start time and duration of each CTA and MCTA are determined by the PNC according to the DEVs' requests and announced in the beacon interval. Each CTA is assigned to an individual DEV. 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 the MCTA. Fig. 2 shows the information delivered by a CTRq command.

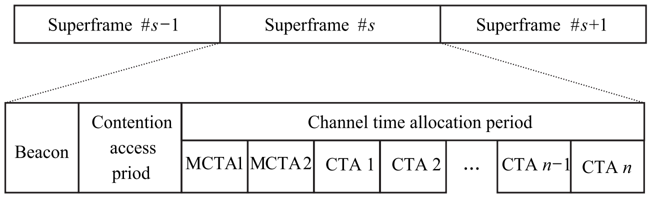

Fig. 1. Superframe structure of IEEE 802.15.3.

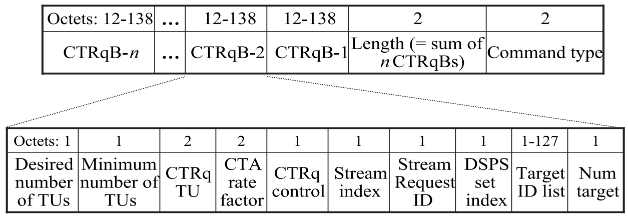

Fig. 2. Channel time request command format and channel time request block field format specified in IEEE 802.15.3.

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). In NO-ACK policy, the receiving DEV does not send back the ACK packet to the sending DEV.

B. PHY Layer and Rate Adaptation

Unlicensed frequency band between 2.4 GHz and 2.4835 GHz is used by the IEEE 802.15.3 physical (PHY) layer. The PHY layer is designed to achieved data rates of 11–55 Mbps that are commensurate with the bitrate of high-definition video and high-fidelity audio. The 802.15.3 systems employ the same symbol rate, 11 Mbaud, as used in the 802.11b systems. Operating at this symbol rate, five distinct modulation formats are specified, namely, uncoded QPSK modulation at 11 Mbps and trellis-coded QPSK, 16/32/64-QAM at 22, 33, 44, and 55 Mbps, respectively.

Rate adaptation is the process of dynamically switching data rates to match the channel conditions, with the goal of selecting the rate that will give the optimum throughput for the given channel conditions. There are two aspects of rate adaptation: 1) Channel quality estimation and 2) rate selection. Channel quality estimation involves measuring the time-varying state of the wireless channel for the purpose of generating predictions of future quality. Rate selection involves using the channel quality predictions to select an appropriate rate. The IEEE 802.15.3 suggests two methods for the rate adaptation. The first method is to periodically transmit the channel status request command to the target DEV. Receiving that command, the target DEV sends a channel status response command back to the transmitting DEV. The channel status response command includes the number of successfully received packets, the number of erroneous packets, and the number of measured packets. The source DEV decides the data rate based on this information. In the second method, the channel condition is evaluated by the presence or absence of ACKs for the transmitted packets. This information is used to decide the data rate for the next packet transmissions. The second method is not applicable to the case of using No-ACK policy. If the Dly-ACK mechanism is used, all packets in a burst are transmitted with the same data rate because of the delayed channel information.

III. PROPOSED PACKET SCHEDULING METHOD

A. Motivation

The channel estimation methods presented in the previous section can not cope with the fast channel changes and may cause incorrect channel information which leads to the performance degradation. Moreover, these estimation methods are futile for traffic which has long packet inter-arrival time, because the transmission history of such a long time period can not represent the current channel condition. Recently, the channel estimation method based on the signal-to-noise ratio (SNR) has been suggested. The evaluation in [12] shows that the method using SNR achieves a higher performance gain than that using the result of attempted transfers of data packets. However, this method requires feedback information from the receiver, which is not applicable to real-time applications without acknowledgements.

The IEEE 802.15.3 TG considers the scenario that DEVs frequently join and leave a piconet as mentioned in [13]. In this scenario, many system parameters such as a superframe length and the number of flows change dynamically. Thus, the association delay becomes a crucial measure in the design of the packet scheduling method.

The packet scheduling method that assigns CTAs for each DEVs plays an essential role to guarantee the QoS of multimedia applications. Nevertheless, the packet scheduling method that considers the multi-layer status is not proposed in the standard and previous literature. Furthermore, 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.

As a consequence, an adaptive cross-layer packet scheduling algorithm is required to support the QoS requirements over these dynamic factors. We propose the packet scheduling method in two steps, basic and adaptive methods.

B. Basic Packet Scheduling

In this subsection, we propose the basic packet scheduling algorithm that allocates CTAs for the packet transmission α_i, and is given by

$$\alpha_i = \frac{P_i}{A_i} \tag{1}$$

where P_i is the packet size and A_i is the packet arrival rate for CBR traffic (or the average packet arrival rate for VBR traffic) in the MAC layer. The values of α_i, P_i, and A_i are calculated by DEV i before the association period and is communicated to the PNC during the association period using the CTRq command. Thus, DEVs have to prepare the value of α_i, P_i, and A_i before the call connection. Reporting inter-arrival time of each flow by each DEV is defined in the standard. CTRq command in Fig. 2 is used.

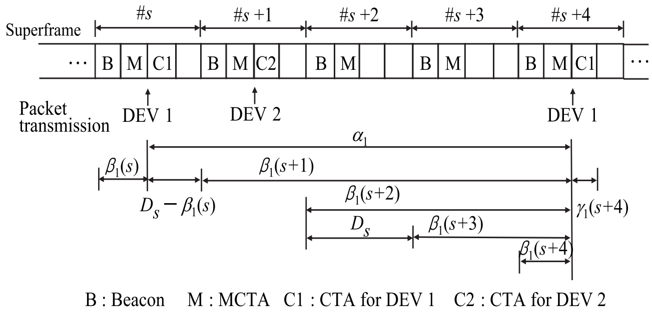

Fig. 3. An example of the basic packet scheduling.

The second parameter for the scheduling algorithm is a timer β_i which has an initial value of α_i. The value of β_i is updated at each superframe and the updated value of β_i at superframe s is denoted by $\beta_i(s)$. The β_i indicates the remaining time interval until the CTA allocation for DEV i. The less β_i, the higher priority the packet scheduler provides for the CTA allocation of DEV i. The PNC selects DEVs whose values of the β_i are less than the time duration of a superframe, D_s. The selected DEVs are called a *candidate set*. Each DEVs in the candidate set is allocated $N_i(s)$ CTAs in superframe s and $N_i(s)$ is given as

$$N_i(s) = \left\lceil \frac{D_s - \beta_i(s)}{\alpha_i} \right\rceil \tag{2}$$

where $\lceil x \rceil$ is the smallest integer value not less than x. Note that $N_i(s)$ is an estimation of the number of packets that will arrive in the interval $D_s - \beta_i(s)$.

For the candidate set, the time duration from the beginning of superframe s to the beginning of the j-th CTA to be allocated, $T_i^j(s)$, is given as

$$T_i^j(s) = \beta_i(s) + (j-1) \times \alpha_i, \quad \text{for } 1 \le j \le N_i(s). \tag{3}$$

Let $r_i(s)$ be the physical layer transmission rate at superframe s. Then, the transmission time for a packet at superframe s, $\gamma_i(s)$, is given as

$$\gamma_i(s) = \frac{P_i}{r_i(s)} + D_{\text{overhead}} + D_{\text{guard}} \tag{4}$$

where D_{overhead} and D_{guard} are the time durations for the overhead and guard time, respectively. Thus, the scheduler assigns a CTA at T_i^j with γ_i duration. Fig. 3 illustrates an example of the parameter update method in the basic packet scheduling. Note that $\beta_1(s) = T_1^1(s)$ and $\beta_1(s+4) = T_1^1(s+4)$ in Fig. 3 where $N_1(s) = N_1(s+4) = 1$. Also note that DEV 1 becomes the candidate set at superframe s and $s+4$.

When two or more scheduled CTAs overlap with each other, the CTA with lower value of T_i^j is allocated in advance. Instead of the value of T_i^j, the scheduler can use other measures for the allocation of the overlapped CTAs such as priority or throughput. In the former case, CTAs of a DEV with higher priority are allocated ahead of those from other DEVs with lower priority. In the latter case, CTAs of a DEV with higher transmission data rate is allocated ahead of one with lower data rate.

We propose the MCTA allocation method as follows. If there is a remaining time interval between two consecutive CTAs,

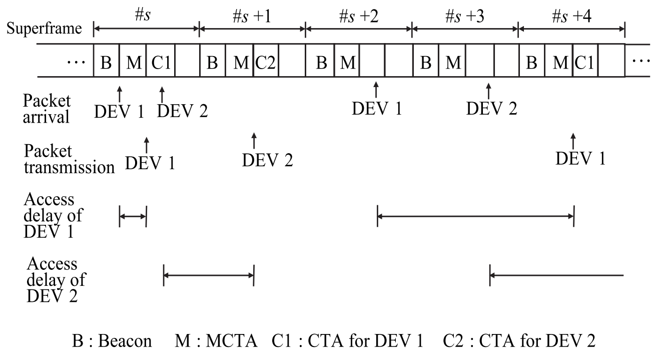

Fig. 4. An example of access delay.

this duration becomes MCTA for transmitting command packets. However, if the remaining time interval 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 a 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_i^j and N_i 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_i^j and N_i. In this case, the selected (real) values for T_i^j and N_i are denoted by t_i^j and n_i, respectively.

As a final step, β_i is updated to the new value for the next superframe formation. The updating method is given by (5).

The first case in (5) corresponds to a DEV whose CTA is not allocated in the current superframe and β_i is subtracted by D_s in the next superframe. The second case shows a DEV that belongs to the candidate set and transmits packets as required. In the third case, when a DEV in the candidate set does not transmit packets as required, it gains higher priority 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.

C. Adaptive Cross-Layer Packet Scheduling

The time duration from the packet arrival at the MAC layer to the transmission of the packet is called *access delay*. Fig. 4 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 communicate the optimal time instant of a CTA, the packet arrival and the CTA are not synchronized. Thus, the average access delay may increase as the packet inter-arrival time increases and it is shown in the next section. Furthermore, it can be longer in heavy load cases since several CTAs overlap. That is, the VBR traffic whose packet inter-arrival time are variable cannot be handled efficiently by using the basic packet scheduling method proposed in the previous subsection. For such traffic type, not only more network conditions need to be considered, but also frequent status update is required. To mitigate these problems, we enhance the basic packet scheduling method as follows.

Table 1. Command packet format for status report.

Octets	10	1	1–4	2	4
Function	MAC header	Report ID	Report payload	Length	FCS

Table 2. List of report IDs and report payload size.

Report type	Report ID	Report payload size (octet)
Q-status	0001	1
Delay	0010	2
Rate	0011	1
Q-status & delay	0100	3(1+2)
Q-status & rate	0101	2(1+1)
Delay & rate	0111	3(2+1)
Q-status, delay, & rate	1000	4(1+2+1)

For VBR traffic, instantaneous bit rate fluctuates widely around a mean value as shown in [14]. Thus, the inter-arrival time at DEV i changes dynamically compared with the statistically calculated α_i. There may be a case where more than one packet are stored in a buffer at the time instant of CTA allocation. If PNC allocates CTAs for VBR traffic using the peak inter-arrival time, the system utilization will be degraded. To achieve better CTA allocation, each DEV should communicate its current status to the scheduler in the PNC.

In our proposed method, during the MCTA, a DEV sends the status information to the PNC by using a *status report command* packet shown in Table 1. The last two subfields in Table 1, length and frame check sequence (FCS), are used for the purpose of the error detection. This command packet specifies three informations for a DEV: Q-status in link layer, access delay in MAC layer, and transmission rate in physical layer. The *report ID* subfield in the status report command indicates one of seven possible report types. The *report payload* subfield is the value of each reporting item. Table 2 lists the report ID and the size of report payload. We denote the latest values of Q-status, access delay, and transmission rate at superframe s as $F_i^Q(s)$, $F_i^D(s)$, and $F_i^R(s)$, respectively.

The access delay feedback information, F_i^D, is used to synchronize the CTA allocation with the packet arrival. When the scheduler receives a status report command with the delay information from DEV i, the value of β_i is subtracted by that delay. Hence, the next CTA for DEV i will be allocated earlier than the previous CTA position since CTA allocation method depends on the value of β_i. Thus, the updating method given in (5) is changed by the access delay and is given in (6).

If the packet arrival rate is constant as CBR traffic, a single status report with the delay information is enough for the PNC scheduler since a DEV with CBR traffic generates one packet in each inter-arrival time. However, for VBR traffic, it is difficult to synchronize the CTA allocation with packet arrival. Thus, we try to reduce the access delay for VBR traffic. In order to decrease

$$\beta_i(s+1) = \begin{cases} \beta_i(s) - D_s, & \text{for } \beta_i(s) \geq D_s,\ N_i(s) = 0 \\ \alpha_i - \Big[D_s - T_i^{N_i}(s)\Big], & \text{for } \beta_i(s) < D_s,\ N_i(s) = n_i(s) > 0 \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

$$\beta_i(s+1) = \begin{cases} \max\big\{0, \beta_i(s) - D_s - F_i^D(s)\big\}, & \text{for } \beta_i(s) \geq D_s,\ N_i(s) = 0 \\ \max\Big\{0, \alpha_i - \Big[D_s - T_i^{N_i}(s)\Big] - F_i^D(s)\Big\}, & \text{for } \beta_i(s) < D_s,\ N_i(s) = n_i(s) > 0 \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

the access delay for VBR traffic, the Q-status of each DEV needs to be reported to the PNC scheduler frequently. This Q-status information, F_i^Q, is transmitted by using the status report command during the MCTA. This information is used to allocate the time duration of each CTA. Thus, the decision method in (4) is modified to

$$\gamma_i(s) = \Big(\frac{P_i}{F_i^R(s)} + D_{\text{overhead}}\Big) F_i^Q(s) + D_{\text{guard}}. \tag{7}$$

We use channel estimation information from the physical layer of the receiver to choose the transmission data rate. In [11], a rate adaptation mechanism for the best effort traffic types such as the bulk file transfer is proposed. Since we are dealing with time-bounded real-time services with No-ACK policy in this paper, a packet to communicate the data rate to the sender is needed. For this purpose, the aforementioned status report command is used to report the selected data rate to the PNC as well as the sender. This command is transmitted during a CAP or MCTA when the currently used rate is not appropriate to meet certain performance criteria like the packet error rate (PER) in [11]–[15]. The channel estimation process is done by the physical layer. This rate feedback information, F_i^R, is utilized for the decision of the CTA durations in (7).

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 a 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.

There may be contention and collision during the status report command transmission. It will occur more frequently as the traffic load becomes heavier. Since, the size of the command packet is small and it is sent only when there is a change from the previous state, the overhead of the command packet is acceptable. Furthermore, by using a more complicated method such as the command packet scheduling, the overhead of the command packet can be alleviated. However, for the sake of the simple implementation and the operational compatibility with the standard, we propose that the command packet is transmitted during a CAP or a MCTA. The simulation results in this paper show that the benefit obtained by using this overhead overcomes the loss by using the overhead.

IV. PERFORMANCE ANALYSIS

For the performance analysis of the proposed method, we use an ideal scenario: Error-free channel, uniformly distributed packet arrival during the superframe period, constant packet inter-arrival time, and no overlapping of packet arrival time.

For the analysis of the mean access delay, we consider the steady state where the association process and the CTA synchronization process are completed. Note that the performance analysis of the mean access delay for VBR traffic is not performed in this paper because of the complexity. The mean access delay for the proposed method, namely adaptive cross-layer WPAN (AC-WPAN), is given as

$$E(T_{acc,i}^{AC}) = 0 \tag{8}$$

because the packet arrival and the CTA are synchronized. On the other hand, the mean access delay for the HR-WPAN is given as

$$E(T_{acc,i}^{HR}) = \frac{1}{2}\,\alpha_i \tag{9}$$

because CTA is uniformly distributed during the packet inter-arrival time. Note that the mean access delay for the HR-WPAN depends on the packet inter-arrival time.

Note that the mean values of the association delays for CBR and VBR traffic are the same. When a DEV wants to transmit the first packet, it has to make a call-connection with the PNC by transmitting the CTRq command packet during MCTA period. The first CTA is allocated after the CTRq command packet is received by the PNC. Let us denote the mean time durations of the beacon, MCTA, and CTA as D_B, D_M, and D_C, respectively. The probabilities that the first packet arrives during the beacon, MCTA, and CTA are denoted by P_B, P_M, and P_C, respectively. Then, the mean association delay for the HR-WPAN is given as

$$\begin{aligned} E(T_{ass,i}^{HR}) &= P_B \times \Big(\frac{D_B}{2} + D_s + D_M\Big) \\ &+ P_M \times \Big(\frac{D_M}{2} + D_s\Big) \\ &+ P_C \times \Big(\frac{D_C}{2} + D_s + D_B + D_M\Big). \end{aligned} \tag{10}$$

The first term in (10) represents the case where the first packet arrives during beacon period. Note that the allocation sequence in a superframe of HR-WPAN is beacon, MCTA, and CTA, as illustrated in Fig. 1. The DEV can transmit the CTRq command during the MCTA period in the same superframe and the first CTA is allocated in the next superframe. In the second term, the first packet arrives during the MCTA period and the CTRq command is transmitted during the same MCTA period. Thus, the first CTA can be allocated in the next superframe. The third term is the worst case for the association delay. The first packet arrives during the CTA period. The transmission of the CTRq command is delayed until the MCTA period of the next superframe. Thus, the first CTA is allocated after the next superframe is finished.

Since the packet arrival is uniformly distributed,

$$P_B = \frac{D_B}{D_s}, \quad P_M = \frac{D_M}{D_s}, \quad P_C = \frac{D_C}{D_s}. \tag{11}$$

If it is assumed that D_B is negligible and $D_s = D_B + D_M + D_C$, (10) becomes

$$E(T^{HR}_{ass,i}) \approx \frac{3}{2}\, D_s. \tag{12}$$

Notice that the mean association delay depends on the superframe duration.

There are multiple MCTAs and E-MCTA in a superframe of the AC-WPAN. Hence the AC-WPAN does not need to wait until the next superframe for the transmission of the CTRq command. Thus, regardless of the arrival time instant of the first packet, the first CTA is allocated in the next superframe. From the assumption of the uniform distribution of the packet arrival instant, the mean association delay for the AC-WPAN is given as

$$\begin{aligned} E(T^{AC}_{ass,i}) &= \frac{1}{2}\, D_s + D_B \\ &\approx \frac{1}{2}\, D_s. \end{aligned} \tag{13}$$

Compared with (12), the AC-WPAN reduces the association delay by 2/3.

V. NUMERICAL RESULTS

A. Simulation Environment

We assume that all DEVs except the PNC are uniformly distributed in the coverage area of a piconet with a diameter of 20 meters. The PNC is located at the center of the area. We consider one piconet in this simulation. The number of DEVs is 11 including the PNC, and the number of flows is the same as the number of DEVs unless otherwise specified. Perfect synchronization in the physical layer is assumed and the propagation delay is not considered. The parameter values used in this simulation study are shown in Table 3. The choice of these values is based on the IEEE 802.15.3 standards [4]. Microsoft Visual C++ 6.0 is used for the simulation tool.

Since the proposed scheme is designed for the time-bounded services, we study two real-time traffic types, the CBR and the VBR in the simulation. The CBR traffic flow is generated at 912 kbps unless otherwise specified. 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 [14] unless otherwise specified. The packet sizes for both traffic are 2048 octets defined in the IEEE 802.15.3 standard. In this simulation, the CAP allocation is not considered since it is optional in the standard.

Table 3. Parameter values.

Parameter	Value
SIFS time	10 μs
Guard time	50 μs
Slot time	17.3 μs
MAC header	10 octets
PHY header	2 octets
Preamble	17.5 μs
HCS	16 bits
FCS	32 bits
Minimum MCTA	3 ms

The scheme proposed in this paper is compared with the HR-WPAN scheme suggested in [6]. The HR-WPAN in [6] adopts an aggressive CTA allocation algorithm. The CTA durations for both the CBR and the VBR traffic flows are evenly allocated over the superframe duration. However, since the VBR traffic may generate more packets than the CBR traffic does, it is unfair to allocate the same CTA durations for both traffic. Therefore, in this simulation, the CTA duration for the VBR traffic is roughly twice as long as that for the CBR traffic. HR-WPAN allocates a MCTA of 3 ms duration as the first CTA in every superframe. Therefore, the duration of each CTA is

$$\frac{D_s - D_B - D_M}{N_C + 2N_V} \times \begin{cases} 2, & \text{for VBR} \\ 1, & \text{for CBR} \end{cases} \tag{14}$$

where N_C and N_V are the number of flows of the CBR and the VBR traffic, respectively. The position of the MCTA in the HR-WPAN does not affect to the performance since no command packet, except the CTRq command, is considered.

Each scenario is simulated for 10 minutes. For the evaluation of the rate adaptation scheme, we simulate 50 different realizations with different positions of DEVs. In every realization, the channel condition for each communication link is recalculated according to the distance between any two DEVs. We use the log-normal shadowing channel model [16]. We set the path loss exponent to 3.3 according to the SG3a alternate PHY selection criteria in [17] and the standard deviation to 7.67 [16]. The transmit power and antenna gain are set to 0 dBm and 0 dBi, respectively, based on [17]. The received SNR is varied by the Ricean fading gain, which is generated according to the modified Clarke and Gans fading model [18].

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 [11].

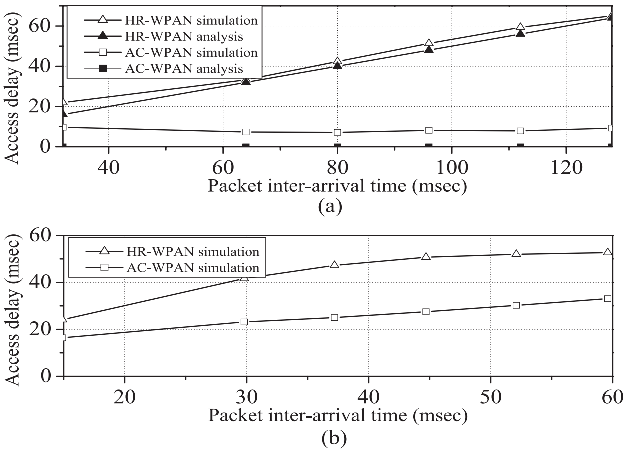

Fig. 5. Effect of the packet inter-arrival time on the mean access delay: (a) CBR traffic, (b) VBR traffic.

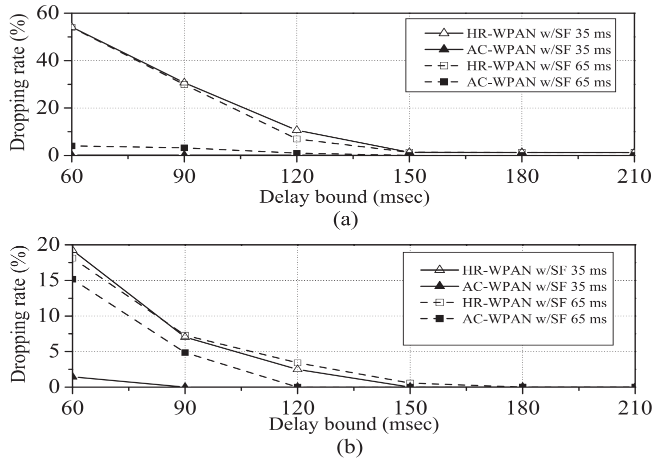

Fig. 7. Effect of the packet delay bound on the packet dropping rate: (a) CBR traffic, (b) VBR traffic.

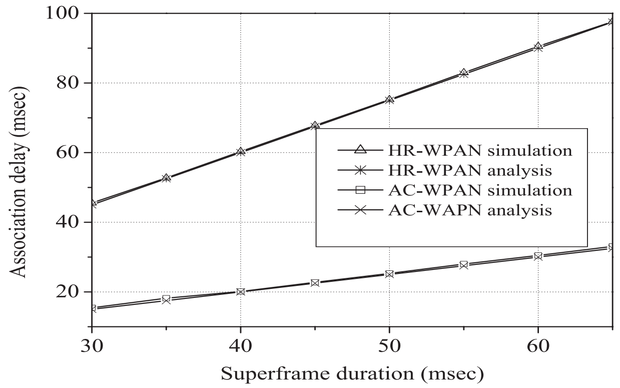

Fig. 6. Effect of the superframe duration on the mean association delay.

B. Simulation Results

The simulation results of the mean access delay are shown in Fig. 5 where the superframe duration is 65 ms. For the simulation, the mean bit rates for the CBR and the VBR traffic are scaled to be commensurate with the packet inter-arrival time. The delay bound is set to the packet inter-arrival time. The packets whose waiting time in the queue are more than the delay bound are discarded. The analytical result for the CBR traffic is compared with the simulation result in Fig. 5(a). The access delay of the AC-WPAN is less than that of the HR-WPAN and is not dominated by the packet inter-arrival time. On the contrary, the access delay of the HR-WPAN increases as the packet inter-arrival time increases. In Fig. 5(b), the access delay for the VBR traffic is larger than that of the CBR traffic. This is because the VBR traffic generates a dynamic traffic load and there exists a difference between the queue status and the allocated CTA duration. However, due to the feedback information and the adaptive scheduling, the access delay of the AC-WPAN is less than that of the HR-WPAN.

For the simulation of the association delay, the connection durations for the CBR and the VBR traffic are exponentially distributed with a mean of 30 seconds. The simulation result of CBR traffic is shown in Fig. 6. Because the simulation results of mean association delay for the CBR and the VBR traffic are the same, the simulation result of the VBR traffic is not shown in this paper. The simulation results for the mean association delay are compared with the analytical results in Fig. 6 and they match well with each other. Though both of them depend on the superframe duration, the AC-WPAN shows shorter association delay than that of the HR-WPAN.

The simulation results of the packet dropping rate for two superframe durations of 35 ms and 65 ms are shown in Fig. 7, where packet inter-arrival time for the CBR and the VBR traffic are 128 ms and 60 ms, respectively. For the CBR traffic, the AC-WPAN shows negligible dropping rate. On the contrary, for real-time traffic that require less than 100 ms delay bound, the HR-WPAN is not adequate because of higher dropping rate. For the VBR traffic, the AC-WPAN also shows lower dropping rate than that of the HR-WPAN. The dropping rate of the AC-WPAN for the 65 ms superframe duration is higher than that for the 35 ms superframe duration. This is because the scheduler has to wait more time to reflect the reported status in the next superframe.

Considering the operational ranges of the interactive real-time traffic, i.e. delay bound is 30$\sim$100 ms and the superframe interval is 4 $\sim$30 ms [7], [9], [19]–[21], the AC-WPAN is a practical solution for the CBR and the VBR traffic. On the contrary, the HR-WPAN is not appropriate for these traffic because of higher packet dropping rate.

Fig. 8 illustrates the packet dropping rate of 35 ms and 65 ms superframe durations as function of the number of flows. For the AC-WPAN, the dropping rates of both traffic are constant at 0%, and slightly increase when there are 20 flows. This is because, in the heavy load case, the CTA allocation may not be synchronized with the packet arrival time due to the overlapped CTAs. On the other hand, the dropping rate of the HR-WPAN increases quickly as the number of flows increases. For the HR-WPAN, the allocated CTA durations reduce with the increasing number of flows so that it is not adequate to transmit all the pending packets. In light load conditions, shorter superframe duration shows less packet dropping rate because the HR-WPAN evenly allocates the CTA duration over superframe duration. In heavy load conditions, shorter superframe duration increases the over-

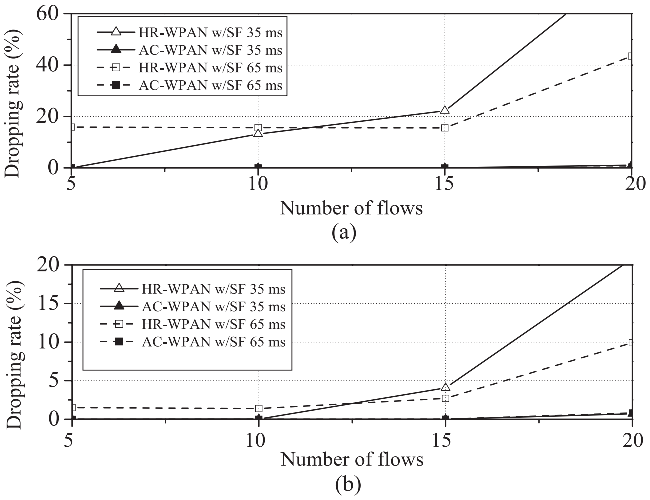

Fig. 8. Effect of the number of flows on the packet dropping rate: (a) CBR traffic, (b) VBR traffic.

head and decreases the effective bandwidth. This results in increased packet dropping rate.

VI. 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 service applications and the QoS are restricted by the system parameters. In this paper, we propose an adaptive cross-layer packet scheduling algorithm for the HR-WPAN to alleviate these design restrictions. The proposed scheme targets on delay-bounded applications in the HR-WPAN. The proposed algorithm initially allocates the CTAs based on the statistical packet inter-arrival time by using the proposed CTRq command. The initially allocated CTAs are dynamically relocated by utilizing the feedback information in order to synchronize the CTA to the packet arrival time and to allocate sufficient time duration for the transmissions of pending packets.

We verify the performance enhancement by the analytical evaluation and 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, the delay bound, and the number of flows. As a result, the proposed method shows less packet dropping rate than that of the HR-WPAN standard for the delay-bounded applications.

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Sung Won Kim received the B.S. and M.S. degrees from the Department of Control and Instrumentation Engineering, Seoul National University, Korea, in 1990 and 1992, respectively, the Ph.D. degree from the School of Electrical Engineering and Computer Sciences, Seoul National University, Korea, in August 2002. From January 1992 to August 2001, he was a researcher at the research and Development Center of LG Electronics, Korea. From August 2001 to August 2003, he was a researcher at the Research and Development Center of AL Tech, Korea. From August 2003 to February 2005, he was a postdoctoral researcher in the Department of Electrical and Computer Engineering, University of Florida, Gainesville, USA. In March 2005, he joined the School of Electrical Engineering and Computer Science, Yeungnam University, Gyeongsangbuk-do, Korea, where he is currently an assistant professor. His research interests include resource management, wireless networks, mobile networks, performance evaluation, and embedded system.

Byung-Seo Kim received the B.S. degree in Electrical Engineering from In-Ha University, InChon, Korea in 1998 and received M.S. and Ph.D. degrees in Electrical and Computer Engineering from University of Florida in 2001 and 2004, respectively. Between 1997 and 1999, he worked for Motorola Korea Ltd., PaJu, Korea as a Computer Integrated Manufacturing (CIM) Engineer in Advanced Technology Research & Development (ATR&D). Since January 2005, he has been with Motorola Inc., Schaumburg Illinois, where he is currently a Senior Software Engineer in Government & Enterprise Mobility Solutions. He has been designing and evaluating an efficient and fast layer-2 handover process for wireless networks for a public safety. His research interests include designing and developing of efficient link-adaptable MAC protocol, cross layer architecture, multi-MAC structure, and resource allocation algorithm for wireless networks.