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Enhanced MAC Protocol for Delay-Constrained Multimedia Services in IEEE802.15.3 Wireless PAN[1]

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Abstract

High-rate wireless personal area network (HR-WPAN) has recently been standardized by the IEEE 802.15.3 Task Group (TG). To support strictly timed multimedia services, the IEEE 802.15.3 TG adopts a time-slotted MAC protocol controlled by a central device. The channel time allocation algorithm, which plays a key role for real time traffics in a centralized TDMA based networks, remains unspecified in the standard. In this paper, we propose a novel feedback-assisted channel time allocation method for HR-WPAN. Channel time for each device (DEV) is initially allocated by a proposed allocation algorithm based on statistical packet inter-arrival time. Then, the initial allocation is dynamically adjusted by utilizing feedback information coming from each DEV. This allocation approach can provide a significant performance improvement. The feedback information includes the buffer status, packet transmission delay, and physical transmission rate. The performance of the proposed scheme remains stable regardless of variable factors such as the number of DEVs and delay bound. To cope with time-varying wireless channels, a dynamic rate selection algorithm assisted by physical layer information is proposed in this paper. Performance evaluations are carried out through extensive simulations and significant performance enhancements are observed.

Keywords: Wireless Personal Area Network (WPAN), Wireless MAC, Link Adaptation.

1 Introduction

Wireless Personal Area Networks (WPANs) being studied by the IEEE 802.15 Working Group (WG) provides short range wireless connectivity among consumer electronics and communication devices. The radio range of WPAN is from 5 to 50 meters

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[1]. 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 [2] recently. The target applications of HR-WPAN can be divided into two categories. The first application is a multi-megabyte data file transfer such as image and music files. The second application is distribution of real-time video and high-quality audio, which are strictly time-bounded applications. To support higher data rates and better Quality of Service (QoS), HR-WPAN adopts a Time Division Multiple Access (TDMA)-based MAC protocol that will be described in Section 2. In HR-WPAN, a pair of nodes can communicate through peer-to-peer connectivity without contention during an allocated channel time. Although the MAC protocol in the IEEE 802.15.3 standard is expected to play a crucial role for the formation of home networks or small office networks, significant efforts for improving the performance of the MAC protocol have not been made since the standard is recently published. Performance enhancements by informing queue-status (Q-status) to a piconet controller (PNC) using MAC header of every packet are shown in [3]. This scheme aims at handling VBR traffics and adopts a flexible superframe size. 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. An algorithm proposed in [4] focuses on utilizing wasted or remaining channel times. The algorithm in [4] uses a constant superframe size. A superframe with two static channel times, one for CBR traffic and the other for real-time VBR (rt-VBR) traffic is used. This scheme also does not consider how to allocate the channel times. The authors in [5] propose a channel time allocation scheme for the specific application, MPEG 4 traffic. Since packets generated from a MPEG 4 encoder are classified into three types and are arranged in 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 [6] because the physical preamble overhead remains as a dominant factor to overcome in the high transmission rate. A rate-adaptive MAC protocol for HR-WPAN is proposed in our previous work [7]. Based on information from a physical layer, the receiver chooses an appropriate data rate and sends it back to the transmitter. The target applications in [7] are asynchronous bursty data transmission requiring an acknowledgement feedback. However, this method is not applicable for real-time services which do not require acknowledgement feedback.

In this paper, we propose an enhanced MAC protocol for HR-WPAN to efficiently support strictly time-bounded services and to adapt the physical transmission rate according to the time-varying channel condition. 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. With the issues in the MAC protocol of the IEEE 802.15.3 standard described, the proposed MAC protocol for HR WPAN is introduced in Section 3. Section 4 describes the simulation environment under which the performance of the proposed protocol is evaluated. Finally, conclusions are provided 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 quality of service (QoS) for delay sensitive applications.

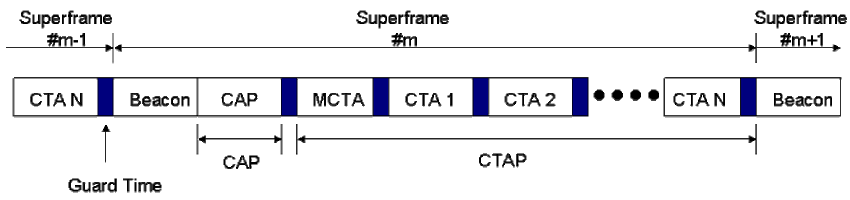

Figure 1: Superframe structure of IEEE $802.15.3$

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 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 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 remaining period in the superframe is CTAP. The CTAP is composed of Channel Time Allocation (CTA) periods and Management Channel Time Allocation (MCTA). The MCTA is also 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 duration of the superframe, CAP, and CTAP based on the DEVs' requests. During one CTA period, one DEV can transmit several packets to one target DEV without collision. Each packet transmission may be followed by an acknowledgement (ACK) packet. A Short InterFrame Spacing (SIFS) idle time is added for a sufficient turnaround time between two consecutive packet transmissions in a CTA. In addition to SIFS, a guard time is required to prevent collision of two adjacent CTAs. The specification for the MAC protocol defines three acknowledgement types: no-acknowledgement (No-ACK), immediate-acknowledgement (Imm-ACK) and delayed-acknowledgement (Dly-ACK).

2.2 Multi-Rate Support

The IEEE $802.15.3$ physical (PHY) layer is operating in the unlicensed frequency band between 2.4 GHz and 2.4835 GHz. The symbol rate is 11 Mbaud. The raw PHY layer data rates are 11Mbps for uncoded QPSK modulation, and $22, 33, 44$, and

55 Mbps for trellis-coded QPSK, 16/32/64-QAM, respectively. The specification in the IEEE 802.15.3 MAC suggests two methods to obtain channel condition information and to select the data rate for transmission. The first method is to periodically transmit the channel status request command to the target DEV. When 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. However, the second method is not applicable for the case of using No-ACK. If the Dly-ACK mechanism is used, all packets in a burst are transmitted with the same data rate.

3 PROPOSED MAC PROTOCOL

3.1 Motivation

The channel time allocation algorithm plays an essential role to guarantee delay bound performance of real-time applications, which HR-WPAN is targeting on. Nevertheless, it is not proposed in the previous literatures. Furthermore, the information delivered by a CTRq command is insufficient for the PNC to decide the duration and location of a CTA for the requesting DEV. The IEEE 802.15.3 TG considers the scenario that DEVs frequently join and leave a piconet as mentioned in [1]. In this scenario, many factors, such as a superframe length and a number of flows, vary in time. As a consequence, the CTA allocation algorithm is required to support the QoS requirements over these variable factors.

The channel estimation methods illustrated in Section 2.2 can not cope with fast channel changes and may cause incorrect channel information which leads to performance degradation. Moreover, for traffics with long packet inter-arrival time, this estimation method are futile since the transmission history for such a long time period can not represent the current channel condition. Recently the use of Signal-to-Noise Ratio (SNR) has been suggested to estimate the channel condition. The evaluation in [8] shows that the method using SNR achieves a higher performance gain than that using the result of attempted transfers of data packets. However, this formal method requires feedback information from the receiver, which is not applicable to real time applications without acknowledgements.

With these considerations, we propose an enhanced MAC protocol for time-bounded services in the next subsections.

3.2 Proposed Protocol for High-Rate Wireless PAN

3.2.1 CTA Allocation algorithm

As mentioned in the previous section, providing delay-bounded services is critical to the real-time traffics and no algorithm to allocate channel times is specified in the standard. Here, we propose a channel time allocation algorithm to synchronize a CTA to the packet arrival instant. We introduce two main parameters that affect the channel time allocation process. The first one is the packet inter-arrival time of DEV i, IA_i. The value of IA_i is the estimated inter-arrival time of packets at DEV i with payload P_i. It is given by

$$IA_1 = \left\lfloor \frac{P_i \cdot 8}{M_i} \right\rfloor, \tag{1}$$

where P_i and M_i are the payload in the MAC packet in bytes and the data arrival rate for CBR traffic (or the mean arrival rate for real-time VBR (rt-VBR) traffic) in the MAC layer at DEV i, respectively. IA_i is calculated by DEV i and informed to the PNC using the CTRq command. For this purpose, the CTA *rate factor* field in the CTRq command is changed to the *Traffic arrival rate* field. We define another parameter Ptr_i, which is related to IA_i in order to allocate CTA for DEV i. Ptr_i is a timer which is initialized to be IA_i and decreased as time elapse. The moment when Ptr_i reaches zero is the time instant to allocate CTA for DEV i. That means that the Ptr_i indicates the remaining time for the CTA allocation for DEV i.

At first, the PNC gathers DEVs whose Ptr_is are less than the current superframe duration since CTAs of those DEVs must be allocated in the current superframe. Therefore, the ensuing steps are applicable only to those DEVs. Then, the PNC decides the number of CTAs which will be allocated in the current superframe. The PNC needs information of $NumCTA_i$, ST_j^j and DT_i^j for each DEV to allocate CTAs in the superframe. $NumCTA_i$ is the required CTAs for a DEV i during a superframe period. It is defined as

$$NumCTA_i = \left\lfloor \frac{T_{SF} - Ptr_i}{LA_i} \right\rfloor + 1, \tag{2}$$

where T_{SF} is the time duration of the superframe.
ST_i^j is the time instant of the beginning of CTA j for DEV i. It is defined as

$$ST_i^j = PTr_i + (j-1) \times LA_i, \;\; i \leq j \leq NumCTA_i. \tag{3}$$

Note that ST_i^j is less than T_{SF}. The time duration of CTA is defined by a current data rate and a number of pending frames. Theses information is informed by each DEV, which will be described in Section 3.2.2. The beacon packet in a superframe has information fields for the location and duration of all CTAs as described in the IEEE $802.15.3$ standard. Thus, the proposed scheme can be implemented without any additional modification to the standard.

Now, CTAs are allocated at time ST_i^j with duration on a superframe. When several CTAs overlap, the CTA with lower ST_i^j is allocated in advance of the one with higher ST_i^j. However, the CTAs can also be allocated based on same specified performance requirements such as priority and throughput. In the former case, CTAs of DEV with higher priority are allocated ahead of those from another DEV with lower priority. In the latter case, CTAs of a DEV with a higher transmission data rate is allocated ahead of one with lower data rate. If there is time remaining between two consecutive CTAs, this duration becomes MCTA for transmitting command packets. However, if the remaining time is less then the threshold T_{thr}, it is merged to previous or next CTA. Therefore, MCTA allocation is also defined. The threshold T_{thr} is a sum of the slot time and the time duration of a CTRq packet. This choice ensures that at least one command packet can be transmitted in the MCTA. The total duration of CTAs and MCTAs allocated in a superframe should be less than T_{SF}. If its total duration is larger than T_{SF}, CTAs at the end will be removed until it is less than T_{SF}.

At the final step, Ptr_i is reset to a value for the next superframe formation. This value is given by

$$Ptr_i = LA_i - (T_{SF} - ST_i^{last}), \tag{4}$$

where ST_i^{last} is the time duration of the lastly allocated CTA for DEV i. For a DEV whose CTAs are not allocated in this superframe, the corresponding Ptr_i is subtracted by T_{SF}.

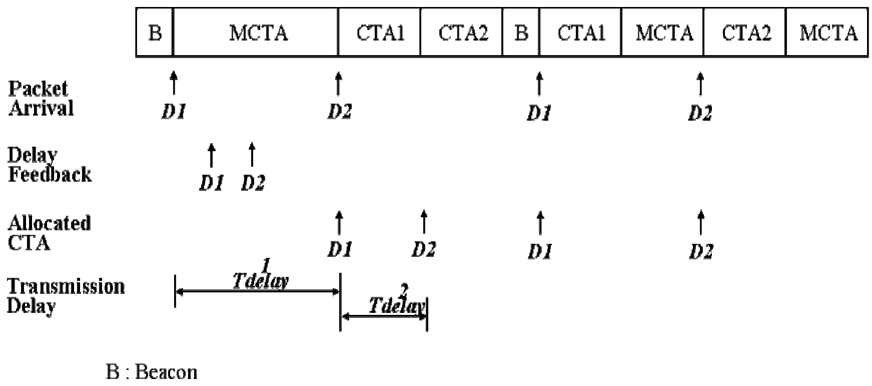

Figure 2: An example of CTA synchronization

3.2.2 Feedback-Assisted CTA Allocation

Employing CTA allocation algorithms based only on statistical packet inter-arrival time is not sufficient to overcome the aforementioned problem for strictly time-bounded services. Since information given by a CTRq command does not include the optimal time instant of a CTA, the PNC may allocate the CTA at any position within a superframe. This causes time wasted from packet arrival at the MAC layer to the transmission of that packet. This wasted time is called transmission delay. Fig. 2 shows an example of transmission delay caused by the lack of information about the actual packet arrival instant at the PNC. This 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. Because of this problem, rt-VBR traffics whose packet inter-arrival time is variable cannot be handled. For rt-VBR traffic, instantaneous bit rate fluctuates widely about a mean value as shown in [11]. As a consequence, the inter-arrival time at DEV i also fluctuates and is different from IA_i statistically calculated by the PNC. That means that more than one packet can be stored in the buffer at the instant CTA allocation. If PNC allocates CTAs for rt-VBR traffic using the peak inter-arrival time, utilization of channel time will be degraded.

Octets: 10	1	1-4	2	4
MAC header	Report ID	Report Payload	Length	FCS

Figure 3: Status report command packet format

To overcome these problems, we propose a feedback-assisted CTA allocation method. To achieve better CTA allocation, each DEV informs its current status to the PNC. For this purpose, during the MCTA, a DEV sends the status information to the PNC by using the *status report* command packet shown in Fig. 3. This command packet specifies three statuses of a DEV: Q-status, delay, and physical transmission rate. The *Report ID* subfield in the status report command indicates one of seven possible report types and the *Report Payload* subfield is the value of each reporting item. Table I lists the *Report ID* and the size of *Report Payload*. When the PNC receives a status report command with the delay information from DEV i, the value of Ptr_i of DEV i at the PNC is subtracted by that delay. Hence, a CTA for DEV i in the next superframe will be allocated earlier than the current CTA position since Ptr_i is shortened by the status report command.

Table 1: 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)

Fig. 2 illustrates an example of the CTA synchronization process with packet arrivals. In the first superframe, DEVs $D1$ and $D2$ have the transmission delays, T^1_{delay} and T^2_{delay}, respectively, which are experienced from previous superframes. The transmission delay information is sent during the MCTA. The PNC changes the time instant of the CTAs in the second superframe. Thus, from the second superframe on, CTAs are located at the packet arrival time instants and the transmission delay becomes zero. If the packet arrival rate is constant as CBR traffic, a single status report with delay information is enough for the PNC scheduler since it a DEV with CBR traffic generates one packet in each inter-arrival time. However, for rt-VBR traffic, this assumption is not guaranteed as mentioned before. In order to dynamically allocate the duration of CTAs for DEVs with rt-VBR, the queue status of each DEV needs to be reported to the PNC scheduler frequently. This queue status information is also transmitted using the status report command during the MCTA. This information is used for allocate the time duration of each CTA.

We use channel estimation information from the physical layer at a receiver to choose the transmission data rate. In our previous work, a rate adaptation mechanism for best effort traffic types such as the bulk file transfer is proposed [7]. On the other hand, since we are dealing with time-bounded real-time services with No-ACK policy here, a packet to inform 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 only when the currently used rate is not appropriate to meet certain performance criteria like the Packet Error Rate (PER) in [7]-[9]. The channel estimation process is done by the physical layer. This feedback rate information is utilized for decision of the CTA durations in the next superframe.

In the 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 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 reflected in the next superframe.

4 Performance Analysis

4.1 Simulation Setting

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 always located at the center of the area. We consider one piconet in this simulation. The parameters used in this simulation study are chosen based on the IEEE $802.15.3$ standards [2].

Since the proposed scheme is designed for the time-bounded services, we study two real-time traffic types, CBR and real rt-VBR in the simulation. The CBR traffic flow is generated at 912 kb/s in [12]. For the rt-VBR traffic model, actual MPRG-4 video streams of Silence of the Lambs with a mean bit rate of 580Kbps and a peak rate of 4.4Mbps, are used [11]. The packet sizes for both traffics are 2048octets defined as the maximum packet size in the IEEE $802.15.3$ standard. The delay bounds of the CBR and rt-VBR traffic are 50 and 70 milisecond, respectively, based on [10]. In this simulation, CAP allocation is not considered since it is optional in the standard [2].

The scheme proposed in this paper, namely Feedback-Assisted WPAN (FA-WPAN), is compared with the HR-WPAN scheme suggested in [3]. HR-WPAN adopts an aggressive CTA allocation algorithm. CTA durations for both CBR and rt-VBR traffic flows are evenly allocated over the superframe duration in the allocation algorithm in [3].

Each scenario is simulated for 10 minutes. For 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 [13]. We set the path loss exponent to 3.3 according to the SG3a alternate PHY selection criteria in [14] and the standard deviation to 7.67 [13]. The transmit power and antenna gain are set to 0 dBm and 0 dBi, respectively, based on [14]. To demonstrate the functionality of the rate adaptation scheme in our proposed protocol, the received SNR is varied by the Ricean fading gain, which is generated according to the modified Clarke and Gans fading model [15].

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 [7].

4.2 Performance Evaluation

In this section, the proposed protocol is evaluated with three superframe sizes, $25, 45, 65$ ms. The maximum superframe size described in the IEEE $802.15.3$ standard is $65536\mu s$.

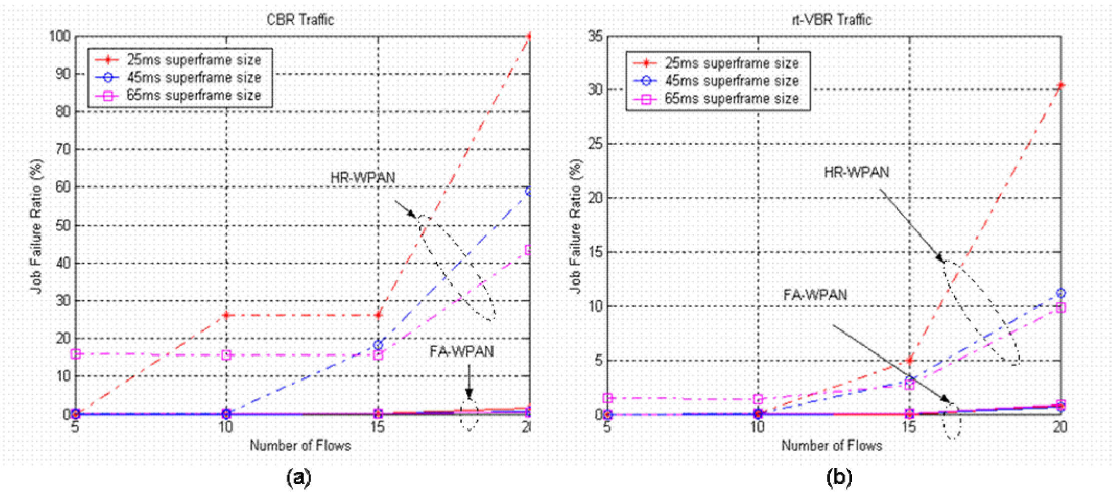

Figure 4: Job failure ratio as a function of the number of flows

Fig. 4 illustrates the JFRs of both configurations as functions of the number of flows. For FA-WPAN, the JFRs of both traffics are constant at 0%, and then slightly increase where there are 20 flows. On the other hand, the JFR of HR-WPAN increases quickly with increasing the number of flows. In the heavy load case, CTA allocation may not be synchronized with the packet arrival time because of overlapped CTAs. For HR-WPAN, the allocated CTA durations reduce with increasing number of flows so that it is not adequate to transmit all pending packets.

Now, the effect of a rate adaptation is evaluated in Fig. 5. In this simulation,

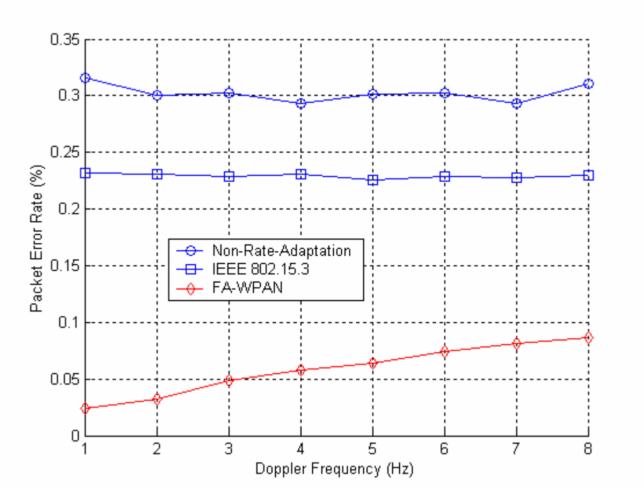

Figure 5: Packet error rate comparisons as a function of Doppler frequency

the superframe size is set to 35 ms. The proposed protocol is compared with two other protocols. The first one is a non-rate-adaptive protocol in which an initially chosen data rate is not changed until the flow is completed. The second one is a rate-adaptive protocol which adopts the transmission rate according to the network performance as described in IEEE $802.15.3$ standard and Section 2.2. Under this protocol, whenever a receiver receives 10 packets, it sends the sender the received packet history such as the number of failed packets. If more than two out of the 10 packets are unsuccessfully transmitted, the sender reduces the next lower data rate. Otherwise, it increases the next higher data rate. In Fig 5, the first and second protocols are labeled as Non-Rate-Adaptation and IEEE $802.15.3$, respectively. The time varying nature of the wireless channel is described by its Doppler spread and coherence time, which are inversely proportional to one another. In our simulation, we consider the effect of the change of the Doppler spread and coherence time with the Ricean parameter $0dB$. Since WPAN is targeting on home or office environment, Doppler frequency varies from 1 Hz up to 8Hz which corresponds to the pedestrian speed of 1m/s. As shown in Fig. 5, the proposed scheme has the lowest PER over the other two schemes. The results illustrates that the other two schemes can hardly adapt to the varying wireless channel. We observe that the PER of FA-WPAN is up to 78% less than that of Non-Rate-Adaptation and 76% less than that of IEEE $802.15.3$.

5 Conclusion

In this paper, we propose a dynamic channel time allocation algorithm. The proposed scheme targets on delay-bounded applications in HR-WPAN. The proposed algorithm initially allocates CTAs based on the statistical packet inter-arrival time by using a proposed CTRq command. The initially allocated CTAs are dynamically relocated by utilizing feedback information in order to synchronize CTA to the packet arrival time and to allocate sufficient channel time for pending packets. We verify the performance enhancement by the extensive simulations. From the simulations, we have shown that the proposed scheme gives significant performance improvements. We note that the performance of the proposed scheme is not influenced by variable factors such as the superframe size, a delay bound, and number of flows. Furthermore, a rate adaptation scheme is proposed to cope with the time varying wireless channel. In the scheme, the rate is selected according to the channel estimation results in the physical layer. The proposed scheme reduces the packet error rate up to 89% of that of the adaptation scheme in the IEEE $802.15.3$.

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