國 立 交 通 大 學

電 信 工 程 學 系

碩 士 論 文

在無線區域網路中
使用擴展性混和協調功能控制型通道存取方式保證服務品質

Scalable HCCA Scheduler for QoS Guarantee in IEEE 802.11e WLANs

研 究 生 ： 葉家豪

指導教授 ： 李程輝 博士

中 華 民 國 九 十 八 年 六 月

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電 信 工 程 學 系 碩 士 班

碩 士 論 文

A Thesis

Submitted to Department of Communication Engineering

College of Electrical and Computer Engineering

National Chiao Tung University

in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in

Communication Engineering

June 2009

Hsinchu, Taiwan

中 華 民 國 九 十 八 年 六 月

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中文摘要

在 IEEE 802.11e 的媒體存取控制中定義了一個新的通道存取機制，Hybrid Coordination Function(HCF)，分配傳送機會(TXOP)給符合服務品質(QoS)需求的工作站。IEEE 802.11e 規格定義的 HCF 控制型通道存取控制(HCCA)參考排程器(Sample Scheduler)，傳送機會的計算是採用平均資料速率對於變動位元速率(Variable Bit Rate)的封包並不適用。一種預測和最佳化控制型通道存取方式(PRO-HCCA)被提出用來處理變動位元速率的封包，把訊務流(Traffic Stream)的延遲限制(Delay Bound)列入考慮，相較於參考排程器，能保證較佳的服務品質。在預測和最佳化控制型通道存取方式排程中，每個訊務流是獨立被輪詢(Polling)，導致有較多的輪詢額外負擔(Overhead)。因此，我們提出了一個修改的機制，每個工作站獨立被輪詢，接著使每個工作站分別有不同的輪詢週期，模擬結果指出我們的方法不但可以達到服務品質的需求，對於頻寬的使用效率上也比預測和最佳化控制型通道存取方式來的好。

Scalable HCCA Scheduler for QoS Guarantee in IEEE 802.11e WLANs

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Abstract

The Medium Access Control of IEEE 802.11e defines a novel coordination function, namely, Hybrid Coordination Function (HCF), which allocates Transmission Opportunity to stations taking their quality of service (QoS) requirements into account. A sample scheduler was provided for HCF Controlled Channel Access (HCCA), a contention-free channel access function of HCF. The sample scheduler is not suitable for VBR traffic because delay bounds are not considered in TXOP allocation. A prediction and optimization-based HCCA (PRO-HCCA) scheduler, which takes delay bounds of different traffic streams into consideration, has recently been proposed to handle VBR traffic. PRO-HCCA was shown to provide much better QoS guarantee than the sample scheduler. The granularity of PRO-HCCA is per traffic stream which causes scalability issue. Besides, each traffic stream is polled individually in every service interval, which implies considerable overhead. Therefore, we present a modified scheme that has per-station granularity and thus is more scalable than PRO-HCCA. To reduce polling overhead, we further modify the scheduler so that different stations can have different polling periods. Numerical results show that our proposed schemes meet QoS requirements and utilize bandwidth more efficiently than PRO-HCCA.

誌謝

感謝指導教授—李程輝老師，兩年來的指導，讓我在每次的開會、私下的討論和待人處事方面都獲益良多，老師和我們間詼諧的對答讓我發現到原來師生間可以這麼的零距離。

感謝親愛的爸爸、媽媽，從小給予我正當的教導，以及精神上的鼓勵，使我能勇往直前朝自己的興趣發展，感謝我兩位活潑的姐姐當我的好榜樣，讓我在求學生活中一直有目標和動力，謝謝我家的愛狗奧斯卡陪著我們一家人十五年，因為有你家裡更加歡樂。

感謝景融學長和郁文學長在無線網路組給了我很多細心的指導和建議，感謝學長姐—迺倫、瑋哥、歪歪、CC 大、世弘、凱文、鑫哥、北極，讓我在懵懂的碩一時期能快速的進入狀況。謝謝同屆夥伴們—佑信、大頭、松晏、鈞傑、小汪、BBN、堯堯，在課業上和生活上都能一起相互扶持。謝謝學弟妹們—小机、小薇、假菜、韋儒、熊仔、世倫，因為有你們的加入，實驗室充滿了歡樂。

謝謝元智大學一起準備研究所的戰友們，當初一起在圖書館奮鬥，成立讀書會，大家最終都考上自己心目中理想的學校，打破電機系有史以來研究所成績最優異的一屆。

謹將此論文獻給所有我愛與愛我的人。

2009 年 6 月於風城交大

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Chapter 1.

Introduction

Wireless networks such as IEEE 802.11 WLANs [1] have recently been deployed widely with rapidly increasing users all over the world. As real-time applications such as VoIP and streaming video are getting more common in daily life, quality of service (QoS) guarantee over wireless networks is becoming an important issue. Generally speaking, QoS includes guarantee of maximum packet delay, delay jitter, and packet loss probability. To cope with this problem, a new enhancement of WLANs, called IEEE 802.11e [2], is introduced to support the QoS requirements of real-time traffic.

Fig.1 shows the example of IEEE 802.11e MAC architecture. The MAC protocol proposes a QoS-aware coordination function which is called Hybrid Coordination Function (HCF). This function consists of two channel access mechanisms. One is contention-based Enhanced Distributed Channel Access (EDCA) for prioritized QoS and the other is contention-free HCF Controlled Channel Access (HCCA) for parameterized QoS. Because of the contention-free nature, HCCA can provide much better QoS guarantee than EDCA [3].

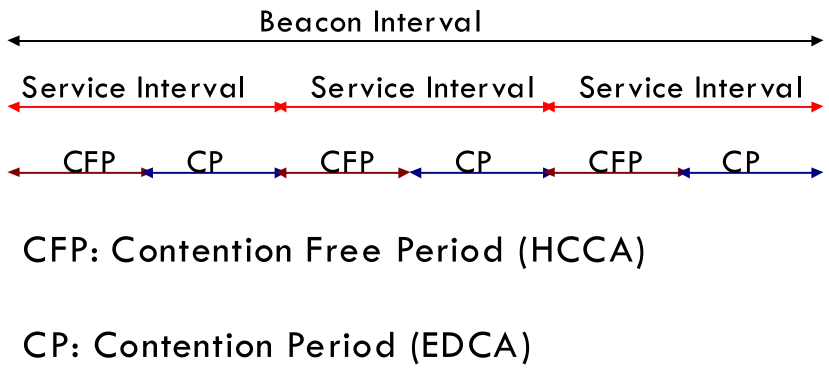

Fig.1. Example of 802.11e MAC architecture

HCCA requires a centralized QoS-aware coordinator, called Hybrid Coordinator (HC), which is commonly located in Access Point (AP). An AP with the HC function is called a QoS-aware AP (QAP). QAP has a higher priority than normal QoS-aware stations (QSTAs) in gaining channel control. QAP can gain control of the channel after sensing the medium idle for a PCF interframe space (PIFS) that is shorter than DCF interframe space (DIFS) adopted by QSTAs. After gaining channel control, QAP polls QSTAs according to its polling list. In order to be included in QAP’s polling list, a QSTA needs to make resource reservation for each traffic stream (TS) attached to it that requires QoS guarantee. Resource reservation is accomplished by sending the Add Traffic Stream

(ADDTS) frame to QAP. In this frame, QSTA can give traffic characteristics a detailed description in the Traffic Specification (TSPEC) field. Based on the traffic characteristics specified in TSPEC and the QoS requirements, QAP calculates the scheduled service interval (SI) and transmission opportunity (TXOP) duration for each admitted TS.

Upon receiving a poll, the polled QSTA either responds with QoS-Data if it has packets to send or a QoS-Null frame otherwise. When the TXOP duration of some QSTA ends, QAP gains control of channel again and either sends a QoS-Poll to the next station on its polling list or releases the medium if there is no more QSTA to be polled.

The TXOP calculation of the sample scheduler provided in IEEE 802.11e standard document is based on mean data rate and nominal MSDU size. It performs well for constant bit rate (CBR) traffic. For variable bit rate (VBR) traffic, packet delay and loss may vary significantly for different TSs. Several schemes have been proposed recently to improve QoS guarantee while maintaining high bandwidth utilization [4]-[13]. As an example, the equal-spacing-based design, a variation of the famous rate monotonic scheduler, was proposed in [12]. In this design, there is no need to have a common SI. Assume that there are *n* TSs and TS *i* is to be served periodically with period T_i. It was shown that all TSs can be served with equal-spacing if and only if 1) $T_{i+1} = k_i T_i$ where k_i is some integer larger than or equal to one and 2) $\sum_{i=1}^{n} TXOP_i / T_i \leq 1$. The equal-spacing-based design is a generalization of the sample scheduler and is only suitable for CBR traffic. A TXOP allocation scheme was proposed in [9] to handle VBR traffic with different delay bound requirements. An equivalent flow with delay bound of one SI is defined for a flow with delay bound of more than one SI to achieve inter-flow multiplexing gain. To reduce computational complexity, authors of [9] assumed that the arrival process of each real-time VBR traffic flow is Gaussian. This assumption may not be valid for real applications. Another design, called prediction and optimization-based HCCA (PRO-HCCA), which can handle VBR traffic was presented in [10], [11]. It takes delay bounds of different TSs into consideration in TXOP allocation. However, the PRO-HCCA scheduler has high implementation complexity because QAP has to maintain a partition list for each TS. Besides, the fact that every TS is polled individually in all service intervals implies considerable overhead for TSs with large delay bounds.

The purpose of this paper is to present a scalable HCCA scheme with per-QSTA granularity. In the proposed scheme, QAP maintains only one partition list for each QSTA even if it is attached with multiple TSs. The proposed scheme is then modified to reduce polling overhead for QSTAs that are attached with TSs having large delay bounds. For the modified scheme, different QSTAs are allowed to have different polling periods. Numerical results obtained from computer simulations show that the proposed HCCA scheme and the modified one perform better than the PRO-HCCA scheduler. Since our designs are related to PRO-HCCA, we shall briefly review the scheduler in Chapter 2.

The rest of this thesis is organized as follows. Chapter 2 describes system model. We also review the sample scheduler and the PRO-HCCA scheduler. Chapter 3 contains our proposed scheduler and we modify our design to allow different polling periods for different QSTAs so that polling overhead can be further reduced. Numerical results are presented and discussed in Chapter 4. Finally, we draw conclusion in Chapter 5.

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Chapter 2.
Related Work

2.1. System model

In the investigated system, transmission over the wireless medium is assumed to be divided into SIs and the duration of each SI, denoted by *SI*, is a sub-multiple of the length of a beacon interval T_b. Moreover, a SI is further divided into a contention period and a contention-free period. We consider only uplink traffic because downlink traffic is completely known to QAP and, therefore, can be easily scheduled.

We assume in this paper that the QoS requirement is specified with delay bound, which can be carried in the Delay Bound field of the TSPEC information. A packet is dropped if it violates the delay bound. There are *N* QSTAs, called $QSTA_1$, $QSTA_2$, …, and $QSTA_N$, with a total of *M* TSs that are numbered from 1 to *M*. There is at least one TS attached to each QSTA. Let D_i be the delay bound of TS *i*. Without loss of generality, we assume that $D_i \le D_{i+1}$, $1 \le i \le M$ -1. During the negotiation process, we request $SI_{\max,i}$ of TS *i* to be $\lfloor D_i / 2 \rfloor$, where $\lfloor x \rfloor$ represents the largest integer smaller than or equal to x. For the rest of this paper, we implicitly assume that $SI_{\max,i}$ is a sub-multiple of T_b. In case $SI_{\max,i}$ is not a sub-multiple of T_b, one can select the largest number smaller than $SI_{\max,i}$ that is a sub-multiple of T_b. The TXOP allocated to $QSTA_i$ for its existing TSs is denoted by $TXOP_i$.

2.2. The Sample Scheduler

Assume that the $(M+1)^{th}$ TS with maximum service interval $SI_{\max,M+1}$ is admitted. In the sample scheduler, QAP determines a possible new SI according to $SI = \min\{SI, SI_{\max,M+1}\}$. QAP then calculates $TXOP_a$ as follows. Firstly, it decides, for TS j, the average number of packets N_j that arrives at the mean data rate ρ_j during one SI

$$N_j = \left\lceil \frac{\rho_j \times SI}{L_j} \right\rceil \tag{1}$$

where L_j denotes the nominal MSDU size of TS j and $\lceil x \rceil$ represents the smallest integer larger than or equal to x. Secondly, the TXOP duration for this TS is obtained by

$$TD_j = \max\left\{N_j \times \left(\frac{L_j}{R} + X\right), \frac{M}{R} + X\right\} \tag{2}$$

where R is the physical transmission rate of $QSTA_a$, and M and X denote, respectively, the maximum allowable size of MSDU and per-packet overhead in time units. The overhead X includes the transmission time for an ACK frame, inter-frame space, MAC header, CRC field and PHY PLCP Preamble and Header.

Finally, the total TXOP duration allocated to $QSTA_a$ which has n_a TSs attached to it is obtained as

$$TXOP_a = \left(\sum_{j=1}^{n_a} TD_j\right) + SIFS + t_{POLL} \tag{3}$$

where $SIFS$ and t_{POLL} are, respectively, the short inter-frame space and the transmission time of a CF-Poll frame.

It is clear that the sample scheduler does not consider delay bounds in TXOP allocation. In other words, it handles all packets of a TS with equal priority. Since the TXOP allocated to a QSTA is constant for all SIs, it is only suitable for CBR traffic.

2.3. The PRO-HCCA Scheduler

The PRO-HCCA scheduler introduces an account mechanism to treat packets generated by TSs according to their urgencies. For each admitted TS *i* with delay bound D_i, QAP maintains a partition list $PL_i = [PL_{i,1}, PL_{i,2}, ..., PL_{i,d_i}]$, where $d_i = \lceil D_i / SI \rceil$ and $PL_{i,j}$ represents the amount of traffic backlogged for time period between $(j-1)*SI$ and $j*SI$. The index *j* in $PL_{i,j}$ indicates the degree of urgency for service. The partition list is updated at each scheduling instant as follows. Consider $PL_{i,j}$ for $j \geq 3$. The value of $PL_{i,j}$ is updated as $PL^0_{i,j-1} - (t^0_{i,j-1} - X)*R$, where $t_{i,j-1}$ is the transmission time allocated to partition *j*-1 during the previous scheduling instant and 0 in the superscript stands for the previous value of the variable. To update $PL_{i,2}$, the amount of traffic arrived during the SI preceding the previous scheduling instant is needed. This information can be derived by QAP if the queue length of TS *i*, denoted by QL_i, is piggybacked in the last frame (or a Null frame if no data of TS *i* is transmitted). The value of $PL_{i,2}$ is updated as $AR^0_i * SI - (t^0_{i,1} - X)*R$, where AR_i is the traffic arrival intensity of TS i and is given by $[QL_i - QL_i^0 + (TXOP_i - X) * R] / SI$, where $TXOP_i$ is the transmission opportunity allocated to TS i during the previous SI. Finally, to obtain the actual value of $PL_{i,1}$, the amount of traffic arrival during the previous SI is required. Unfortunately, this information is unknown to the QSTA before the end of the previous SI. As a result, a prediction scheme was adopted to estimate the traffic intensity PR_i. The wavelet transform-based LMS (least mean square) [14] predictor was adopted to reduce the eigenvalue spread and achieve good performance. The following Algorithm 1 summarizes the update procedure for partition list PL_i.

Algorithm 1: Update procedure for partition list PL_i

```
for i = 1 to M
    for j = ⌈D_i / SI⌉ downto 3
        PL_{i,j} = PL^0_{i,j-1} - (t^0_{i,j-1} - X) * R        (4)
    endfor
    PL_{i,2} = AR^0_i * SI - (t^0_{i,1} - X) * R
    PL_{i,1} = PR_i * SI
endfor
```

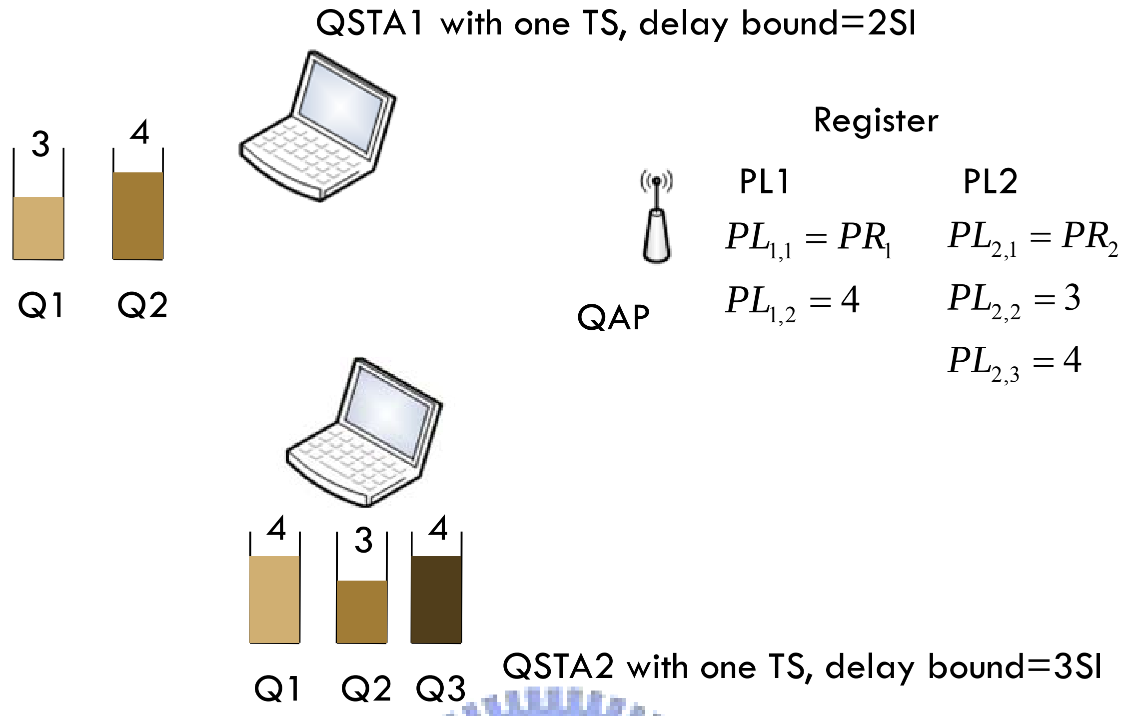


Fig.2. Example of the PRO-HCCA scheduler

Fig.2. shows the example of PRO-HCCA scheduler. There are two QSTAs, and each of QSTA attached one TS. The delay bound of TS attached to $QSTA_1$ is 2SI, and $QSTA_1$ maintains two queues to store different urgency packets. In the same way, $QSTA_2$ maintains three queues to store different urgency packets. In QAP part, QAP maintains two partition lists for these TSs and allocates TXOP according these partition lists.

The TXOP allocation was formulated as the classical fractional Knapsack problem [15]. Let T_{CP} represent the time assigned to EDCA traffic within a beacon interval. Further, let $T_{avail} = \max(\rho_{hcca} * SI, dot11CAPLimit)$, where $\rho_{hcca} = (T_b - T_{CP})/T_b$ and $dot11CAPLimit$ is the minimum time assigned to a controlled access phase which is determined during the WLAN setup. Note that T_{avail} represents the amount of medium time that can be used by the admitted TSs. For simplicity, we assume in this paper that $T_{avail} = \rho_{hcca} * SI$. The transmission time allocation problem was modeled as

$$
\begin{aligned}
&\text{maximize} \sum_{i=1}^{M} \sum_{j=1}^{d_i} U_{i,j} t_{i,j} \\
&\text{s.t.} \sum_{i=1}^{M} \sum_{j=1}^{d_i} t_{i,j} \le T_{avail} \\
&0 \le t_{i,j} \le (PL_{i,j} / R + X),\ i = 1,2,\ldots,M;\ j = 1,2,\ldots,d_i.
\end{aligned}
\tag{5}
$$

In the above model, the variable $U_{i,j} = 1/(d_i - j + 1)$ represents the utility received from transmitting data belonging to partition $PL_{i,j}$ for a single time unit. Clearly, more urgent data are handled with higher priority than less urgent data in the model. In other words, the transmission order is determined by the earliest deadline first policy. The TXOP allocated to TS i is given by $\sum_{j=1}^{d_i} t_{i,j}$.

Note that the per-TS granularity of the PRO-HCCA scheduler may create scalability issue in a WLAN with a large number of TSs, because QAP has to maintain a partition list for each TS. Besides, the fact that each TS is polled in every service interval induces significant polling overhead for TSs with large delay bounds. In the next chapter, we present our proposed Scalable PRO-HCCA scheduler which has per-QSTA granularity.

Chapter 3.

Our Proposed Scheme

3.1 The Scalable PRO-HCCA Scheduler

3.1.1 How to choose SI

Let $D_{\min}$ and $D_{\max}$ denote, respectively, the minimum and maximum delay bounds of all possible applications. Define the minimum service interval SI_m as $SI_m = \lfloor D_{\min}/2 \rfloor$. For simplicity, we assume that $D_i = d_i * SI_m$, where d_i is an integer which satisfies $2 \le d_1 \le d_2 \le \ldots \le d_M$ and $D_{\max} = Max * SI_m$. As in the sample scheduler, the service interval SI chosen by QAP is equal to $SI_{\max,1}$. For the rest of this section, we let $SI = d * SI_m$. Besides, whenever a particular QSTA is considered, it is assumed to be $QSTA_p$ and there are K TSs with delay bounds $b_1 * SI_m$, $b_2 * SI_m$, …, and $b_K * SI_m$ attached to it. We assume that $b_1 < b_2 < \ldots < b_K$. Note that two TSs attached to the same QSTA can be merged into one if they have the same delay bound.

3.1.2 QSTA queue management

Consider $QSTA_p$. To support the proposed scalable PRO-HCCA (SPRO-HCCA) scheme, $QSTA_p$ needs to implement Max queues. For convenience, these queues are numbered from 0 to $Max-1$. All the Max queues are in use and shared by the K TSs attached to $QSTA_p$ no matter what value SI is. For queue *i*, there is an associated register Q_i which saves the amount of data currently residing in the queue. A pointer Ptr, which points to queue 0 initially, is used in operation. Given d, queues Ptr, $Ptr+1 \pmod{Max}$, …, and $Ptr+d-1 \pmod{Max}$ contain data, if any, that have to be served in the current service interval to avoid violating their delay bounds and being dropped. For the rest of article, we omit the modulo Max operation and assume that it is performed implicitly.

3.1.3 QSTA operation

For QSTAs, an SI is divided into d sub-intervals of equal length SI_m. Consider $QSTA_p$ and a particular SI. For all *k*, $1 \le k \le K$, the data generated by TS k in the j^{th} $(1 \le j \le d)$ sub-interval of the considered SI are placed in queue $Ptr + b_k + j - 1$. Let $A_{k,j}$ denote the amount of data generated by TS k in the j^{th} sub-interval. The register Q_{Ptr+b_k+j-1} is updated as $Q_{Ptr+b_k+j-1} = Q_{Ptr+b_k+j-1} + A_{k,j}$ at the end of the j^{th} sub-interval. Finally, at the end of the considered SI, $QSTA_p$ updates, for all *i*, $Q_i = Q_i - r_i$, where r_i is the amount of data in queue *i* that are served in the SI, and then sets $Ptr = Ptr + d$. Data that violate their delay bounds are dropped. The associated register of a queue with dropped data is updated accordingly. Figure 3 shows an example for $Max = 8$, $d = 2$, $K = 1$, $d_1 = 4$, and $Ptr = 4$ at the beginning of the n^{th} SI. In this example, we assume equal-length packets with $A_{1,1} = 2$ (packets) and $A_{1,2} = 1$ in the n^{th} SI. As illustrated in the middle part of Fig. 3, Q_0 is updated as $Q_0 + 2$ at the end of the first sub-interval, assuming that no data stored in queue 0 are served in the SI. At the end of the second sub-interval (which is also the end of the SI), Q_1 and Ptr are updated as $Q_1 + 1$ and $Ptr + 2$, respectively, as shown in the bottom part of Figure 3.

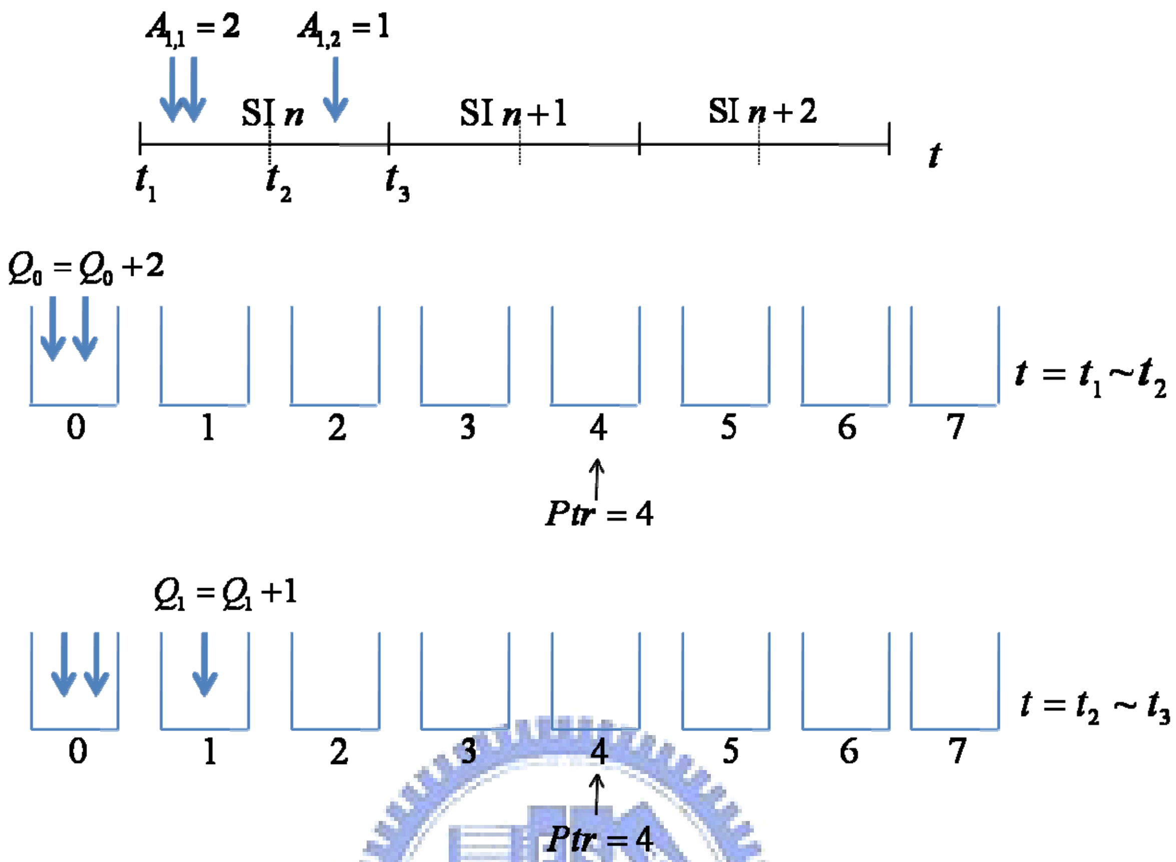


Fig. 3. Example of QSTA operation with Max=8, d=2, K=1, d1=4, and Ptr=4

3.1.4 QAP maintains Partition List for each QSTA

Given d, QAP maintains for $QSTA_p$ a partition list denoted by $G_{p,1}, G_{p,2}, \ldots,$ and $G_{p,h}$, where $h = b_K / d$. To simplify the notation, we use G_i to represent $G_{p,i}$. The content of G_i is deemed by QAP the amount of data stored in $QSTA_p$ which will violate their delay bounds if not served in the next i SIs. For convenience, we assume that there is a virtual G_{h+1} whose content is always zero. Consider a particular SI. Let e_k represent the average rate of data generated by TS k, $1 \le k \le K$, and $E_k = e_k * SI$.

Further, let t_i be the amount of data in G_i that is served during the considered SI. At the end of the SI, the content of G_i is updated as follows. QAP sets $G_{a_i} = G_{a_i+1} - t_{a_i+1} + E_i$, $1 \le k \le K$, where $a_i = b_i / d$, and $G_i = G_{i+1} - t_{i+1}$ if $i \ne a_j$ for any *j*, $1 \le j \le K$. Note that we use mean as an estimate of data generated by each TS to reduce computational complexity. One of the new G_i values will be replaced by the value reported by $QSTA_p$ described below.

3.1.5 Reporting Mechanism

A reporting mechanism is adopted to let every QSTA report its queue occupancy to help QAP allocate TXOP better. The reporting mechanism is designed as follows. Consider $QSTA_p$ in the n^{th} SI. In the last data frame (or Null frame), the value $U = Q_{Ptr+fd} + Q_{Ptr+fd+1} + ... + Q_{Ptr+(f+1)d-1}$ as well as *f* are piggybacked to QAP, where *f* (≥ 1) is the smallest integer such that queue $Ptr + fd$, $Ptr + fd + 1$, ..., or $Ptr + (f+1)d - 1$ is the first queue after queue Ptr which received new data since it was reported last time. If no such queue exists, then $QSTA_p$ reports $U = f = 0$. Initially, all queues are considered as reported simultaneously and QAP sets $G_i = 0$ for all *i*,

$1 \le i \le h$. At the end of the n^{th} $(n \ge 1)$ SI, QAP changes G_f to U or does nothing if $U = 0$. Figure 4 illustrates an example for $Max = 8$, $K = 2$, $d = 2$, $d_1 = 6$, $d_2 = 8$, and $Ptr = 0$. For this example, we have $h = d_2 / d = 4$. Initially, the partition list maintained in QAP satisfies $G_i = 0$, $1 \le i \le 4$. Assume that the TXOP allocated to $QSTA_p$ in the first SI is zero. Assume further that during the first SI, TS 1 generates one packet in each sub-interval and TS 2 generates one packet in the second sub-interval. If the TXOP allocated to $QSTA_p$ in the second SI is only enough to transmit a packet, then the reported value is $U = 1$ and $f = 2$, as shown in the middle part of Figure 4. Note that Ptr is 2 at the beginning of the second SI. Upon receiving the reported values, QAP updates $G_2 = 1$. Assume that the TXOP allocated to $QSTA_p$ in the third SI is zero and, moreover, in the second SI, TS 1 generates two packets in the first sub-interval and zero packet in the second sub-interval and TS 2 does not generate any packet. As a result, as illustrated in the bottom part of Fig. 4, the value reported by $QSTA_p$ in the third SI is $U = 3$ (which consists of one packet generated by TS 2 in the first SI and two packets generated by TS 1 in the second SI) and $f = 2$. After receiving the reported information, QAP updates $G_2 = 3$.

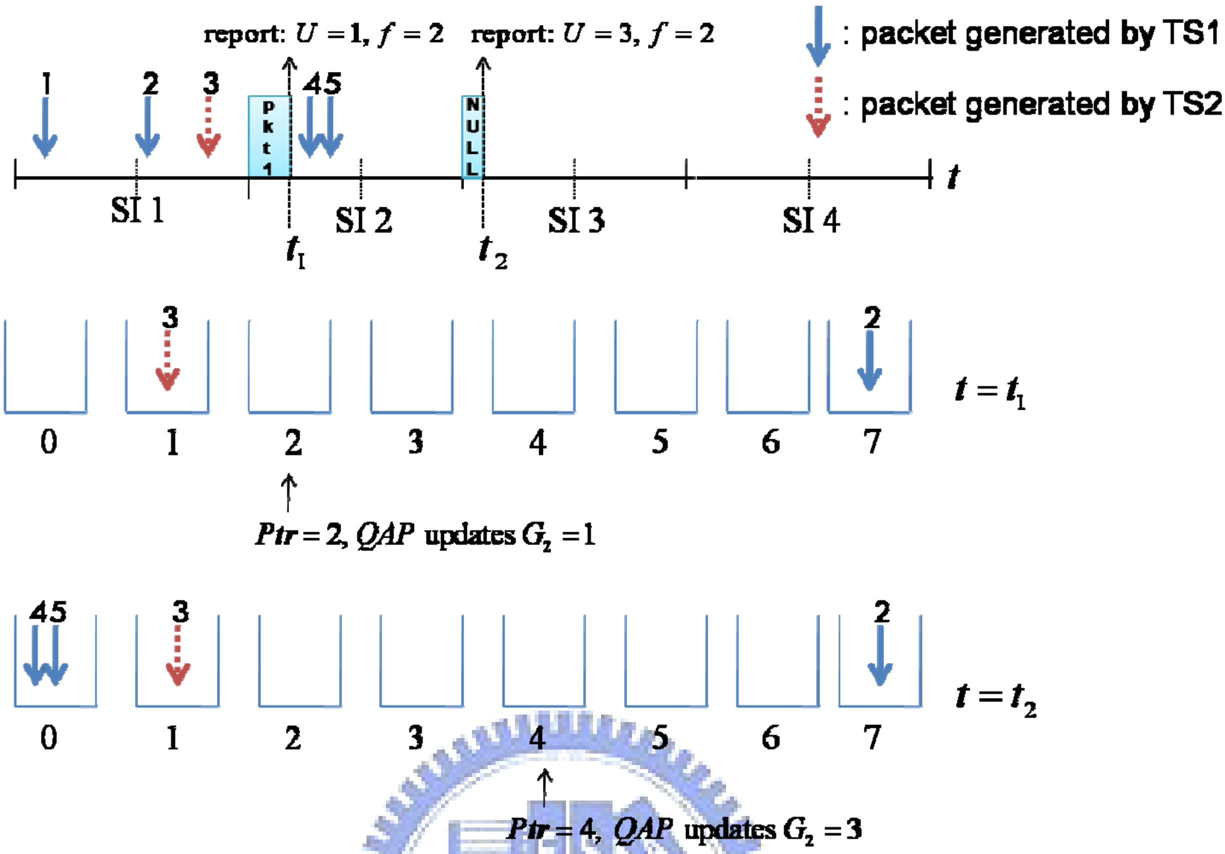


Fig. 4. Example of reporting mechanism for *Max*=8, *d*=2, *K*=2, d_1=4, d_2=8, and *Ptr*=0

3.1.6 When SI is changed

Note that SI could be changed if a new TS is admitted or an existing TS is finished. Consider now the situation when SI is changed. Assume that d is changed to d'. Since all Max queues are in use, there is virtually no impact on STA operation. The only work is to replace d with d'. As for QAP, it needs to compute the new values of the partition list for each QSTA. Consider $QSTA_p$ and let G'_i, $1 \le i \le b_K / d'$, be the new partition list maintained for $QSTA_p$. Let z be the least common multiple of $\{h, s\}$ such that $z = ch = c's$, where $s = b_K / d'$. QAP computes $g_{i+(j-1)c} = G_j / c$ for

$1 \le i \le c$ and $1 \le j \le h$. The new G_i' is then obtained as $G_i' = \sum_{j=1}^{c'} g_{j+(i-1)c'}$, $1 \le i \le s$.

Figure 5 shows an example of splitting the partition list. Initially, the partition list has three parts, i.e.: *h*=3. When a new TS is admitted, the SI is changed and the partition list is split into four parts in this example, i.e. *s*=4. How does QAP achieve this goal? QAP first calculate the values *z*=12, *c*=4 and *c'*=3. Each part of the original partition list first split into four parts, and every three parts merge into one part. Therefore, the new partition list has four parts and QAP allocates TXOP to each QSTA according to the new splitting partition list.

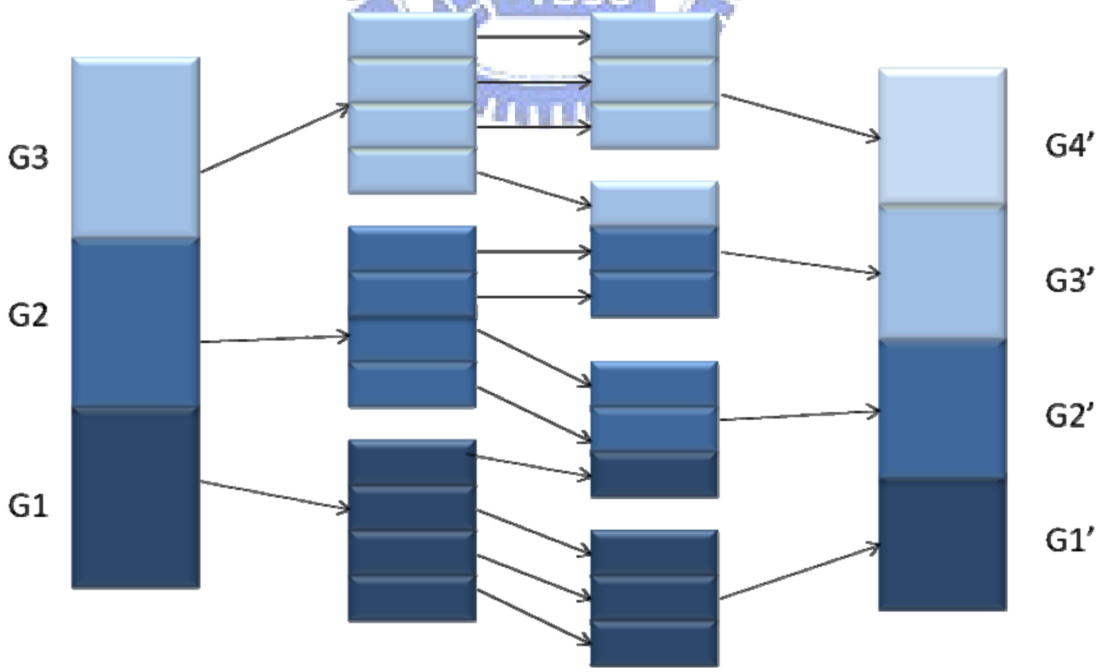


Fig. 5. Example of splitting the partition list

3.1.7 TXOP allocation to each QSTA

The TXOP allocation problem in our proposed SPRO-HCCA scheme is the same as that in the original PRO-HCCA scheme except that TXOPs are allocated to QSTAs instead of individual TSs. That is, the same classical fractional Knapsack problem is solved. However, the variable $t_{i,j}$ represents the transmission time allocated to data belonging to partition $PL_{i,j}$ of $QSTA_i$. Because of per-STA granularity, the computational complexity of the proposed SPRO-HCCA scheme can be much smaller than that of the PRO-HCCA scheme if *M* is much larger than *N*. Besides, QAP needs to maintain only one partition list for each QSTA even if there are multiple TSs attached to the QSTA.

$$\text{maximize} \sum_{i=1}^{N}\sum_{j=1}^{h} U_{i,j} t_{i,j}$$

$$\text{s.t.} \sum_{i=1}^{N}\sum_{j=1}^{h} t_{i,j} \le T_{avail} \qquad (6)$$

$$0 \le t_{i,j} \le (PL_{i,j}/R + X),\ i = 1,2,...,N; \quad j = 1,2,...,h$$

The TXOP allocated for $QSTA_k$ is

$$TXOP_k = \sum_{j}^{h} t_{kj},\ \ k = 1,2,\cdots,N \qquad (7)$$

3.2 Reducing Overhead SPRO-HCCA

3.2.1 Reducing the polling overhead

While maintaining the advantage of reporting, it is possible to reduce polling overhead of a $QSTA$ if every TS attached to it has a delay bound greater than or equal to four SIs. Consider $QSTA_p$ and let $q_p = \lfloor b_1/(2*d) \rfloor$. To reduce overhead, QAP can poll $QSTA_p$ once every q_p SIs. For example, assume that $SI = SI_m$ and $b_1 = 4$. For this example, $QSTA_p$ is polled once every two SIs. We call $q_p * SI$ = $q_p * d * SI_m$ the polling period of $QSTA_p$. The idea can be applied to all QSTAs. Let $q_i * SI$, $1 \le i \le N$, denote the polling period of $QSTA_i$. That is, $QSTA_i$ is polled by QAP once every q_i SIs. As a result, different QSTAs may have different polling periods. The operations of $QSTA_i$ and QAP with respect to $QSTA_i$ are the same as those described in the last section as long as the polling period $q_i * SI$ is treated as SI.

Figure 6 shows the different polling period of different QSTAs. In this example, there are three QSTAs, and polling period are SI, 2SI, and 3SI. The polling list period maintain by QAP is $LCM(1,2,3)=6$.

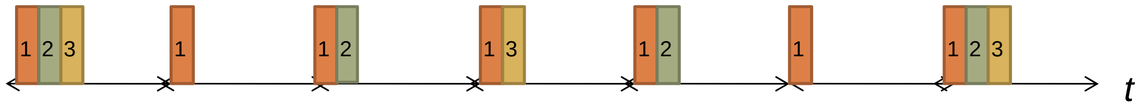


Fig. 6. Example of different polling period of different QSTAs

3.2.1 Reducing the Partition List

Clearly, the partition list is still a source of complexity. One way to simplify the partition list as follows. Consider $QSTA_p$. It always reports the value $U = (\sum_{j=0}^{q_p*d-1} Q_{Ptr+q_p*d+j})/R$ to QAP. The partition list maintained by QAP for $QSTA_p$ has only two elements, i.e., $G_{p,1} = U$ and $G_{p,2} = (\sum_{i=1}^{K} e_i * q_p * SI)/R$. Note that $G_{p,2}$ is the average transmission time of traffic arrivals to $QSTA_p$ in one polling period and is constant unless the TSs attached to $QSTA_p$ are changed. The same idea can be applied to all QSTAs. Consequently, there are only two elements in the partition list of every QSTA.

3.2.2 Find the service start point

Since a QSTA could be polled once every several SIs, we need to decide how the QSTAs are polled. Define $AL_i = G_{i,2}$, $1 \le i \le N$, as the average load in transmission time offered by $QSTA_i$ in one polling period. Let $P_N = LCM(q_1, q_2, ..., q_N)$ be the least common multiple of $\{q_1, q_2, .., q_N\}$. Time is divided into frames so that each frame consists of P_N SIs. The SIs in a frame are numbered from 1 to P_N. QAP maintains a polling list for each SI. It is clear that the polling lists are periodic with period P_N and, therefore, the total number of polling lists maintained by QAP is P_N. Note that the polling lists can be efficiently represented as a binary tree if $q_i = 2^{k_i} * SI_m$ for all *i*, $1 \le i \le M$, where k_i is a non-negative integer.

The polling lists are constructed as follows. To add the first $QSTA$ to the polling system, QAP decides $SI = SI_{\max,1}$, sets $P_1 = 1$, and puts $QSTA_1$ to the polling list for each SI. Assume that the polling lists are constructed for the existing *N* QSTAs and a new QSTA, i.e., $QSTA_{N+1}$, is to be added to the system. Let TL_i be the total average load offered by the QSTAs in the polling list of SI *i*. Assume that D_{N+1} does not change SI. The procedure to add $QSTA_{N+1}$ to the polling system is as follows. QAP first computes $P_{N+1} = LCM(P_N, q_{N+1})$. Then it determines l_j = $\max_{0 \le k \le (P_{N+1}/q_{N+1})-1} \{TL_{j+k*q_{N+1}}\}$ for $1 \le j \le q_{N+1}$. After that, QAP finds i = $\arg\min_{1 \le j \le q_{N+1}} \{l_j\}$. $QSTA_{N+1}$ is added to the polling lists of SIs $i + k * q_{N+1}$ for all

k, $0 \le k \le P_{N+1} / q_{N+1} - 1$. If D_{N+1} causes change of SI, then the new SI is smaller than the original value. In this case, the construction procedure is performed for $QSTA_1$, $QSTA_2$, ..., and $QSTA_{N+1}$ one by one with the new SI. Obviously, a similar procedure can be performed to update the polling lists if q_k is changed for some k, $1 \le k \le N$, due to change of TSs attached to $QSTA_k$.

Figure.7. shows the example of adding a new QSTA and updating the polling list maintained by QAP. In Figure.7 (a), there are existing three QSTAs with polling periods SI, 2SI, and 3SI and QAP maintains a polling list with period 6SI. A new $QSTA_4$ with polling period 4SI is added to the system. In Fig.7 (b), QAP first determines the new polling list period P_{N+1}=12 and compute the total traffic load of each polling list. In Fig.7 (c), QAP picks up the maximum traffic load of each label, and determines the service start point that is the minimum traffic load we pick up. In this example, we pick up label 2 in Fig. 7(d), and the new QSTA is polled according the new updating polling list.

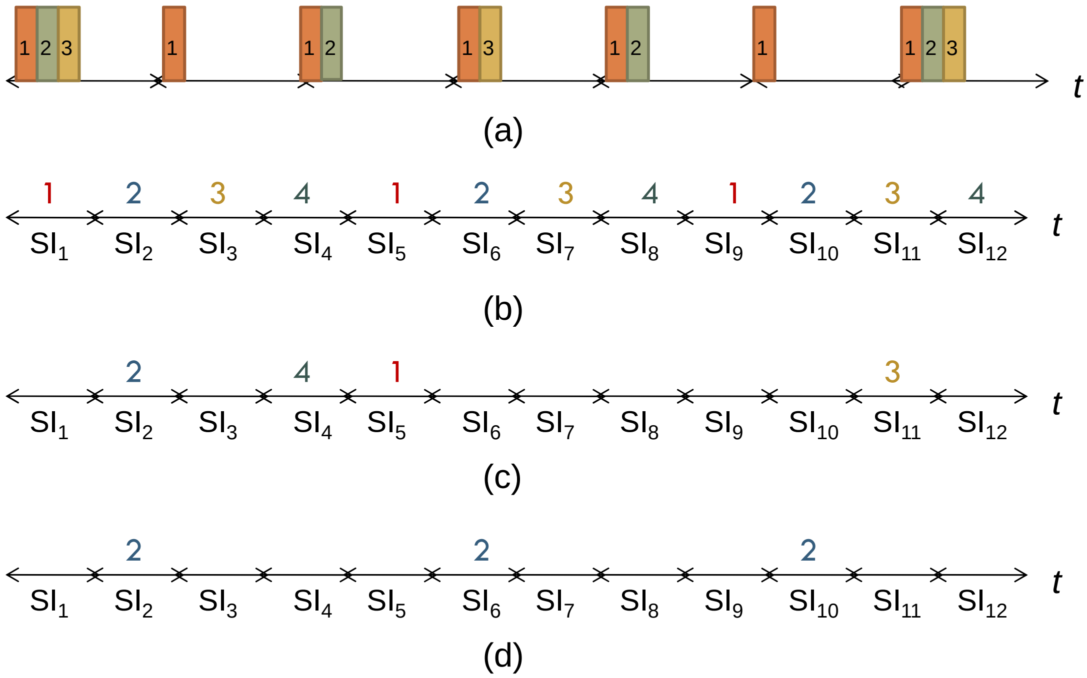


Fig. 7. Example of updating the polling list

Chapter 4.

Experimental Result

The PHY and MAC parameters and all related information used in simulations are shown in Table I. Note that the sizes of QoS-ACK and QoS-Poll in the table only include the sizes of MAC header and CRC overhead. We assume that the minimum physical rate is 2Mbps and t_{PLCP} is reduced to 96 μs. It is assumed that $SI_m = 10$ ms. Two types of TSs, with characteristics and QoS requirements shown in Table II, are considered in simulations. Type I and Type II TSs are lecture room cam and interactive video, respectively. We assume that 90% of the bandwidth is used by HCCA, i.e., ρ_{hcca}=0.9.

Table I. Related parameters used in simulations.

PHY and MAC parameters	
SIFS	10 us
MAC Header size	32 bytes
CRC size	4 bytes
QoS-ACK frame size	16 bytes
QoS CF-Poll frame size	36 bytes
PLCP Header Length	4 bytes
PLCP Preamble length	20 bytes
PHY rate(R)	11 Mbps
Minimum PHY rate (R_{min})	2 Mbps
Transmission time for different header and per-packet overhead	
PLCP Preamble and Header (t_{PLCP})	96 µs
Data MAC Header (t_{HDR})	23.2727 µs
Data CRC (t_{CRC})	2.90909 µs
ACK frame (t_{ACK})	107.63636 µs
QoS-CFPoll (t_{POLL})	122.1818 µs
Per-packet overhead (X)	249.81818 µs

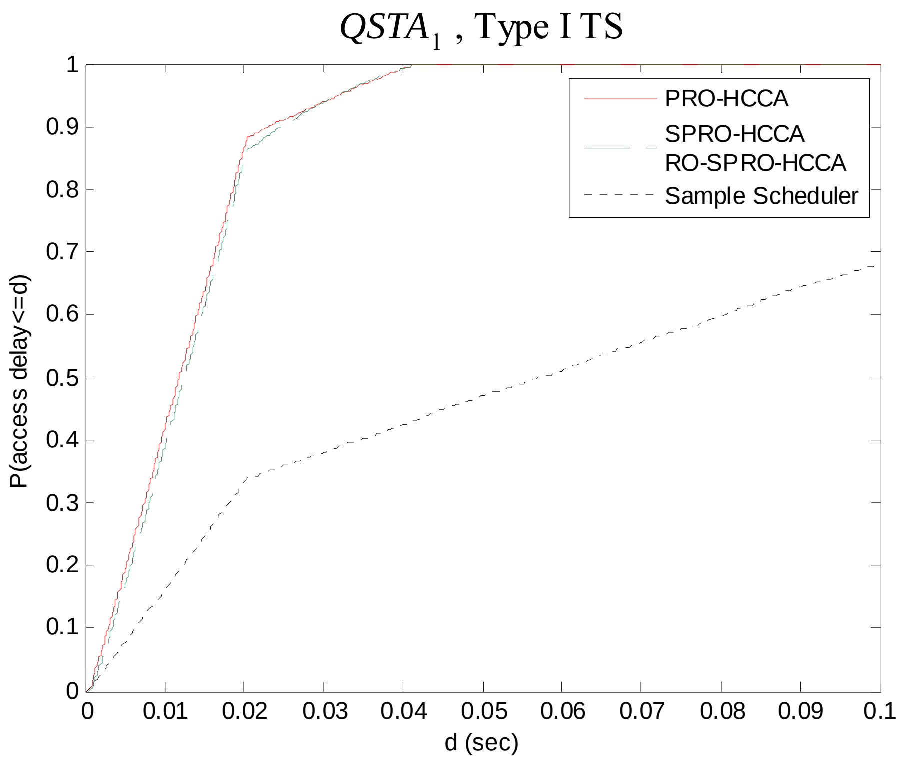
Table II. TSPECs for two different types of traffic flows.

Traffic characteristics and QoS requirements	Type I	Type II
Maximum Service Interval	20 ms	40 ms
Delay Bound	40 ms	80 ms
Mean Data Rate	42 Kbps	246 Kbps
Nominal MSDU size	211 bytes	1232 bytes
Scheduled Service Interval	20 ms	

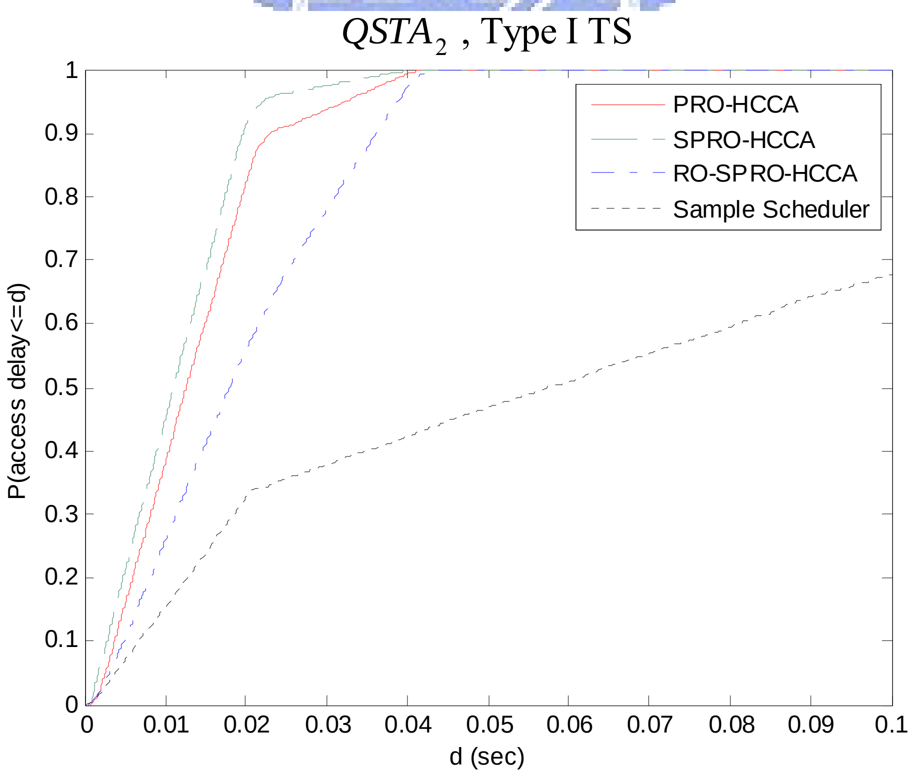
In the first experiment, we compare the performances of the sample scheduler, the PRO-HCCA scheduler, the SPRO-HCCA scheduler, and the reduced-overhead SPRO-HCCA (RO-SPRO-HCCA) scheduler with real traces [17]. There are three QSTAs. $QSTA_1$, $QSTA_2$, and $QSTA_3$ that are attached with two Type I TSs, one Type I TS and another Type II TS, and two Type II TSs, respectively. As a result, the scheduled SI is set to 20 ms = $2SI_m$. The polling order is $QSTA_1$, then $QSTA_2$, followed by $QSTA_3$. In the PRO-HCCA scheme, for the two TSs attached to $QSTA_2$, the Type I TS is polled before the Type II TS. Because of the 80 ms delay bound, Type II TSs attached to $QSTA_3$ are polled once every two SIs in the RO-SPRO-HCCA scheme.

Figs. 8(a)-8(d) show the cumulative distribution functions (CDFs) of delay for TSs attached to various QSTAs. Note that, as illustrated in Fig. 8(a), the RO-SPRO-HCCA scheme is the same as the SPRO-HCCA scheme for the TSs attached to $QSTA_1$. One can see in Fig. 8(a) that packets of TSs attached to $QSTA_1$ experience roughly the same delay under the SPRO-HCCA scheme and the PRO-HCCA scheme. The curves shown in Fig. 8(b) reveal that packets of Type I TS attached to $QSTA_2$ experience smaller delay under the SPRO-HCCA scheme than the PRO-HCCA scheme. The reason is that packets of Type I TS have smaller delay bound than packets of Type II TS and, therefore, under the SPRO-HCCA scheme, may use the bandwidth allocated to packets of Type

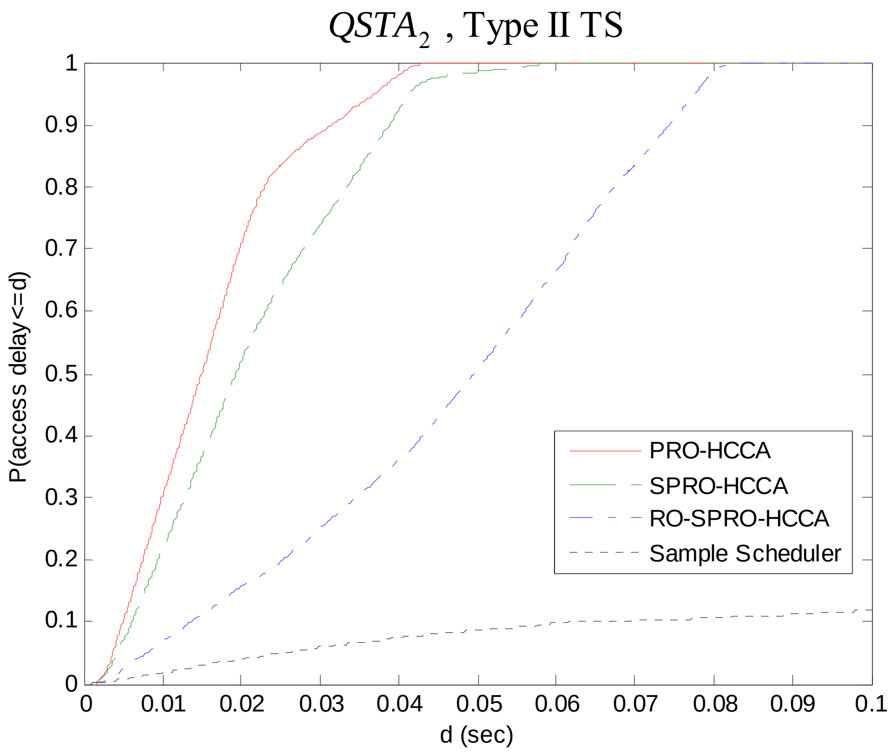
II TS that can be kept for more than two SIs. Because of this, packets of the Type II TS experience larger delay under the SPRO-HCCA scheme than the PRO-HCCA scheme, as can be seen in Fig. 8(c). Note that the RO-SPRO-HCCA scheme is different from the SPRO-HCCA scheme for $QSTA_2$. There are four entries for the partition list maintained for $QSTA_2$ under the SPRO-HCCA scheme. However, under the RO-SPRO-HCCA scheme, there are only two entries for the partition list maintained for $QSTA_2$ and only the data that will violate their delay bounds if not served in the next SI are reported to QAP. Packets experience more delay under the RO-SPRO-HCCA scheme than under the SPRO-HCCA scheme and the PRO-HCCA scheme. However, all packets meet their delay bounds. The sample scheduler obviously cannot meet QoS requirements. Although the PRO-HCCA, SPRO-HCCA, and RO-SPRO-HCCA schedulers meet QoS requirements, their ratios of overhead transmission time to total transmission time are different. They are 34.92%, 31.40%, and 29.51% for the PRO-HCCA, SPRO-HCCA, and RO-SPRO-HCCA schemes, respectively.


QSTA1 , Type I TS
P(access delay<=d)
d (sec)
PRO-HCCA
SPRO-HCCA
RO-SPRO-HCCA
Sample Scheduler
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

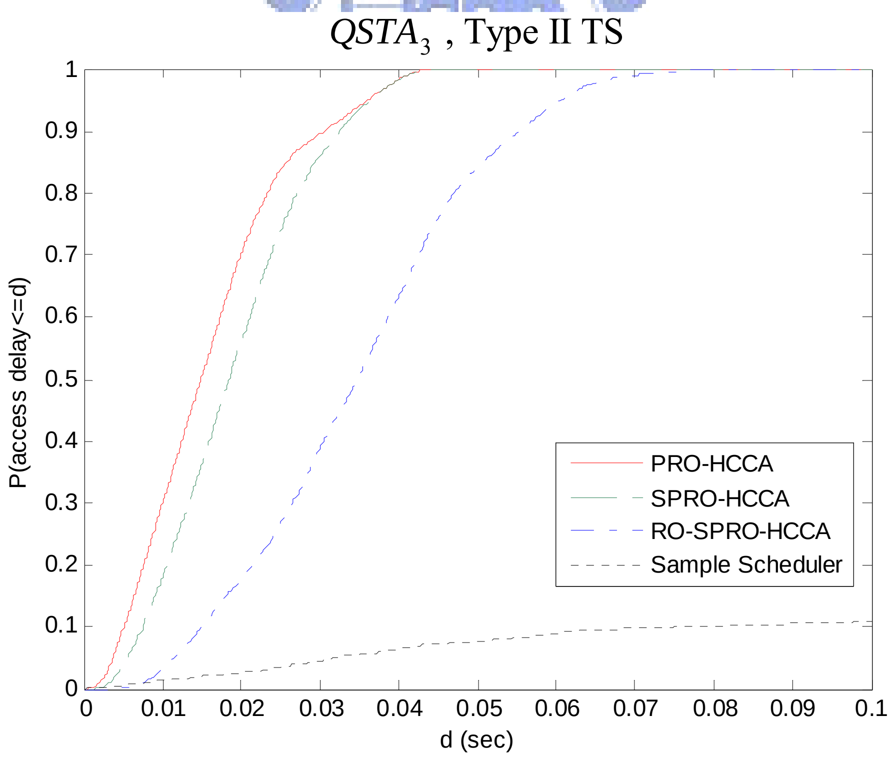
(a)


QSTA2 , Type I TS
P(access delay<=d)
d (sec)
PRO-HCCA
SPRO-HCCA
RO-SPRO-HCCA
Sample Scheduler
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

(b)



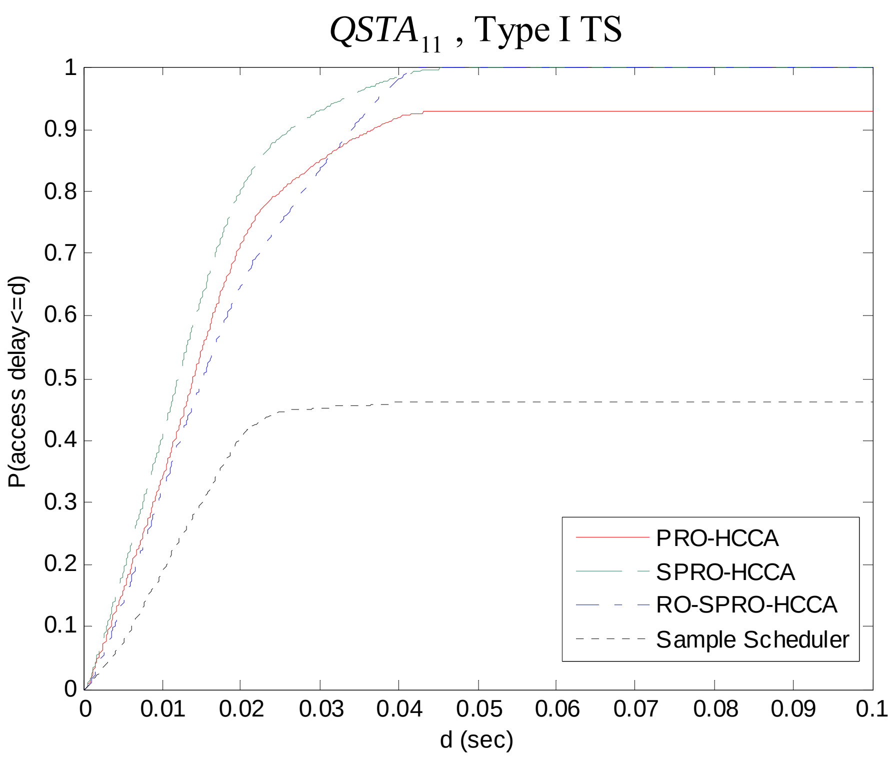
(c)



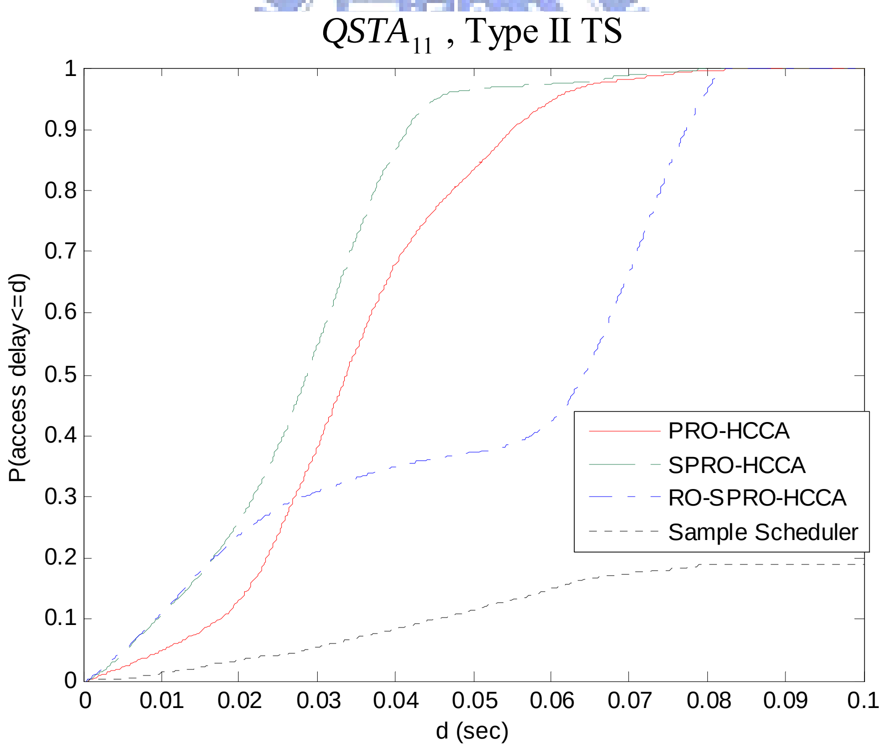
(d)

Fig. 8. Performance comparison of various schedulers for three different QSTAs.

In the second experiment, we assume that there are one Type I TS and one Type II TS attached to each QSTA. Simulations are performed to determine the maximum number of QSTAs N that can be supported without violating delay bound requirements under the SPRO-HCCA scheme. The result is $N = 11$. Therefore, we simulate a system which consists of 11 QSTAs under various scheduling schemes. QSTAs are polled one by one. In the PRO-HCCA scheme, Type I TS is polled before Type II TS attached to the same QSTA. Note that, similar to the situation of $QSTA_2$ in the first experiment, the RO-SPRO-HCCA scheme is different from the SPRO-HCCA scheme for this experiment. Figs. 9(a) and 9(b) show, respectively, the CDFs of delay for packets of Type I TS and Type II TS attached to the eleventh QSTA. As one can see from the figures, the SPRO-HCCA scheme outperforms the PRO-HCCA scheme for both types of TSs. The phenomenon we observed for $QSTA_2$ in the first experiment, i.e., the bandwidth allocated to less urgent packets of Type II TS could be used by packets of Type I TS, does not appear in the second experiment. The reason is that almost all bandwidth are allocated to the most urgent packets that will be dropped if not served in the next SI. Some packets violate their delay bounds and are lost under the PRO-HCCA scheme because it suffers from higher overhead than the SPRO-HCCA scheme. The packet loss probabilities due to violation of delay bounds are summarized in Table III. The low packet loss probabilities make the RO-SPRO-HCCA an attractive scheme for real systems.



(a)



(b)

Fig. 9. Performance comparison of various schedulers for eleven identical QSTAs.

Table III. Packet loss probabilities for various schedulers.

TS type of QSTA 11 / Scheduler	Type I TS	Type II TS
PRO-HCCA	7.11%	0.2%
SPRO-HCCA	0%	0%
RO-SPRO-HCCA	0.15%	0.13%
Sample Scheduler	53.92%	81.04%

Chapter 5.

Conclusion

We have presented in this paper a per-QSTA based scalable TXOP allocation scheme for HCCA to guarantee QoS for VBR traffic in WLANs. The scheme is modified to allow different polling periods for different traffic streams. Computer simulations with real traces show that our proposed schemes meet QoS requirements. Besides, according to simulation results, our proposed schemes utilize bandwidth more efficiently than the sample scheduler and the PRO-HCCA scheduler. An advantage of the proposed schemes is that they do not require traffic models. It suffices to know the mean arrival rate of each traffic stream. Simplicity and robustness make the proposed schemes good candidates of the TXOP allocation scheme for HCCA to guarantee QoS for variable bit rate traffic streams.

Bibliography

[1] IEEE 802.11 WG: IEEE Standard 802.11-1999, Part 11: Wireless LAN MAC and Physical Layer Specifications. Reference number ISO/IEC 8802-11: 1999(E), 1999.

[2] IEEE Std. 802.11e-2005, Part 11: Wireless LAN medium access control and physical layer specifications Amendment 8: medium access control (MAC) quality of service enhancements, Nov. 2005.

[3] S. Mangold, S. Choi, G. R. Hiertz, et. All, "Analysis of IEEE 802.11e for QoS support in Wireless LANs," IEEE Wireless Commun., vol. 10, no. 6, pp. 40-50, Dec. 2003.

[4] P. Ansel, Q. Ni, and T. Turletti, "FHCF: A fair scheduling scheme for IEEE 802.11e WLAN," INRIA research report, no. 4883, Jul. 2003.

[5] Y. Higuchi, A. Foronda, C. Ohta, M. Yoshimoto and Y. Okada, "Delay guarantee and service interval optimization for HCCA in IEEE 802.11e WLANs," in Proc. IEEE WCNC 2007.

[6] A. Annese, G. Boggia, P. Camarda, L. A. Grieco, and S. Mascolo, "Providing delay guarantees in IEEE 802.11e networks," in Proc. WWIC 2005.

[7] W. F. Fan, D. Y. Gao, D. H. K. Tsang and B. Bensaou, "Admission Control for variable bit rate traffic in IEEE 802.11e WLANs," in Proc. IEEE LANMAN 2004.

[8] Y. W. Huang, T. H. Lee and J. R. Hsieh, "Gaussian approximation based admission control for variable bit rate traffic in IEEE 802.11e WLANs," in Proc. IEEE WCNC 2007.

[9] T. H. Lee and Y. W. Huang, "Effective transmission opportunity allocation scheme for real-time variable bit rate traffic flows with different delay bounds," IET Commun., vol. 2, no. 4, pp. 598-608, 2008.

[10] M. M. Rashid, E. Hossain, V. K. Bhargava, "HCCA scheduler design for guaranteed QoS in IEEE 802.11e based WLANs," in Proc. IEEE WCNC 2007.

[11] M. M. Rashid, E. Hossain, V. K. Bhargava, "Controlled channel access scheduling for guaranteed QoS in 802.11e-based WLANs," IEEE Trans. Wireless Communications, vol. 7, no. 4, Apr. 2008.

[12] Q. Zhao and D. Tsang, "An equal-spacing-based design for QoS guarantee in IEEE 802.11e HCCA wireless networks," IEEE Trans. Mobile Computing, vol. 7, no. 11, Nov. 2008.

[13] H. Fattah and C. Leung, "An overview of scheduling algorithm in wireless multimedia networks," IEEE Wireless Commun., vol. 9, no. 5, pp. 76-83, Oct. 2002.

[14] B. Farhang-Boroujeny, Adaptive Filters: Theory and Applications. New York: Wiley, 1998.

[15] T. Cormen, C. Leisorson, R. Rivest, and C. Stein, Introduction to Algorithms, Second Edition. Cambridge, MA: MIT Press, 2001.

[16] J. Choe and N. B. Shroff, "A central limit theorem based approach for analyzing queue behavior in high-speed networks," IEEE/ACM Trans. Networking, vol. 6, no. 5, pp. 659-671, Oct. 1998.

[17] MPEG-4 and H.263 video traces for network performance evaluation, http://www.tkn..tu-berlin.de/research/trace/trace.html, Oct. 2006.

D. S. Kim, H.-N. Nguyen, T. Thein, and J. S. Park, "An Optimized

Intrusion Detection System Using PCA and BNN," *in Proc. Information and Telecommunication Technologies*, 6th Asia-Pacific Symposium, p.p. 356-359, 10-10 Nov. 2005