Delay Guarantee and Service Interval Optimization for HCCA in IEEE 802.11e WLANs

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Abstract—**IEEE 802.11e Medium Access Control (MAC) is a supplement to the IEEE 802.11 Wireless Network (WLAN) standard to support Quality of Service (QoS). The 802.11e MAC defines a new coordination function, namely Hybrid Coordination Function (HCF), which takes the QoS requirements of flows into account and allocates Transmission Opportunity (TXOP) to stations. On the basis of mean sending rate, delay of Variable Bit Rate (VBR) traffic cannot be bounded with the reference HCF scheduling algorithm proposed in this supplement. In this paper, we propose a new scheduling algorithm that utilizes the token bucket and a modified Latency-Rate (LR) scheduling algorithm to guarantee a bounded delay for HCF Controlled Channel Access (HCCA). The new Service Interval (SI) is calculated to optimize the number of stations accommodated and takes into account delay bound and token bucket parameters. We show that is possible to obtain worst-case performance guarantees on delay. First, we analyze the behavior of the proposed scheduler with a loss free wireless channel model and after this, with a burst loss model and we explain how it is possible to extend this scheduler for a multi-rate scheme. Properties of the proposal are investigated both theoretically and using ns-2 simulations. We present a set of simulations with both Constant Bit Rate (CBR) and VBR flows and performance comparisons with HCF scheduling algorithm. The results show that the delay upper bound can be achieved for a large range of networks load with bandwidth optimization.**

I. INTRODUCTION

In recent years, IEEE 802.11 WLAN [1] has emerged as a popular technology for wireless access. Moreover, the need for wireless multimedia transmission services is continuously growing [2].The IEEE 802.11 protocol has established as a standard in wireless LANs, however it provides support only for best-effort service.

In order to support applications with QoS requirements, such as phone or videoconference over IP networks, the IEEE 802.11 Working Group has proposed the new IEEE 802.11e [3] to provide the IEEE 802.11 MAC with two additional access mechanisms: Enhanced Distributed Channel Access (EDCA) and HCCA.

HCCA is used to provide a parameterized QoS service. EDCA provides only a QoS priority differentiation via a random distributed access mechanism [4] [5], while HCCA guarantees that the QoS requirements are met once a stream has been admitted into the network.

The main goal of this work is to optimize the number of stations accommodated in one SI and to guarantee a required bounded delay. Then, we develop a delay bound analysis considering the use of a modified LR server [6] [13] combined with token bucket admission control [7]. We estimate the optimal SI to allocate a maximum number of TSs according to the token bucket parameters, maximum delay required by an STA, packet size and physical rate. Required delay bound is compared with the results of the simulations to evaluate the model. The new scheduler is compared with the reference HCF scheduler, described in the next section. Then, we consider a burst loss model to analyze the behavior of the new scheduler and we introduce the multi-rate scheme and explain how to adapt it to the new scheduler. Simulation results show that the new scheduler is able to guarantee delay bounds required by applications and optimize the number of connections in the network.

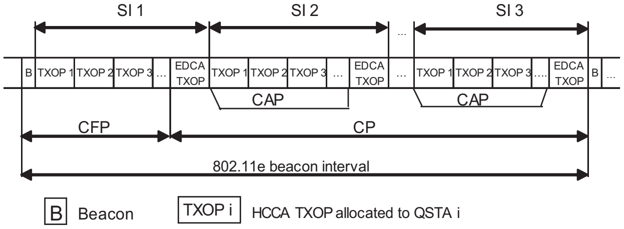

Fig. 1. IEEE 802.11e beacon interval

The remainder of this paper is organized as follows. In Sect.II, we describe the IEEE 802.11e HCF and related work. In Sect.III, we present the new scheduler and the analytical model to bound delay. Next, we present the simulation experiments. Finally, we conclude the paper in Sect.V.

II. IEEE 802.11E HCF AND RELATED WORK

HCF is the new MAC protocol of the 802.11e standard. In HCF, contention-based EDCA and polling-based HCCA are no longer separated, and EDCA is defined as a part of HCF.

HCCA method has been proposed by the 802.11e working group [3] in order to provide parameterized QoS support regardless the traffic conditions. Figure 1 shows the HCCA frame. After an optional period of Contention-Free Period (CFP), there is a part namely Contention Period (CP), where EDCA and HCCA, which is used in Controlled Access Period (CAP), alternate in a beacon interval.

Before a data transmission, a traffic stream needs first to be established and each QoS Station (QSTA) sends a QoS

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request frame containing the corresponding Traffic Specification (TSPEC) to the QAP. TSPEC contains application mean data rate, MSDU size, maximum SI, delay bound, token bucket size, token bucket rate and others parameters. Upon receiving all the requests, the QAP determines the minimum value of all SIs required by the different traffics which apply for HCCA. Then it chooses the highest sub-multiple of the superframe duration (duration between two beacons), which is the minimum of all the SIs.

However, HCF reference scheduler only specifies application mean data rate, MSDU size and maximum SI and thus, the scheduler with these parameters, calculates the number of packets arriving in the traffic stream during selected SI and computes the allocated $TXOP_i$ for each traffic stream *i* as shown in (1) and (2):

$$N_i = \lceil \frac{\lambda_i SI}{L_i} \rceil, \tag{1}$$

$$TXOP_i = \max\left(\frac{N_i L_i}{R} + O, \frac{M_i}{R} + O\right), \tag{2}$$

where λ_i is the mean application data rate, L_i is the nominal MSDU size from TSPEC, *SI* is the service interval, *R* is the physical transmission rate, M_i is the maximum MSDU size and *O* is the overhead in time units.

An admission control algorithm is also suggested in the HCF algorithm. The admission control admits a stream if it satisfies the following inequality:

$$\frac{TXOP_{k+1}}{SI} + \sum_{i=1}^{k} \frac{TXOP_i}{SI} \leq \frac{T - T_{\mathrm{CP}}}{T}, \tag{3}$$

where *k* is the number of existing streams and *k*+1 is used as the index for the newly arriving stream. *T* indicates the beacon interval and T_{CP} is the time used for EDCA access.

It is shown in [8] that the HCF scheduling algorithm is only efficient for flows with CBR characteristics. Several real time applications, such as VBR video traffic have small variations in their packet sizes or sending rates. Reference HCF scheduler may be efficient to bound delay if TXOPs are allocated according to the maximum sending rate of a VBR flow but, in this case, few flows can be accepted in HCCA. Thus, they proposed a new HCF scheduling algorithm, Fair HCF Scheduling (FHCF) algorithm for 802.11e WLAN, which aims to be efficient for both CBR and VBR flows. However, FHCF cannot provide a bounded delay for these flows or estimate an optimal TXOP to allocate more stations.

Other related works [9]-[12] as well as above try to guarantee certain level of QoS to the input traffic. However, they do not analyze how to optimize the bandwidth in the wireless network. Therefore, the proposed scheduler is the first to provide a delay bound and bandwidth optimization for HCCA in IEEE 802.11e wireless network. We focus our schedule in the uplink, that means the direction of transmission is from QSTA to QAP. This is the same approach followed by all the related works.

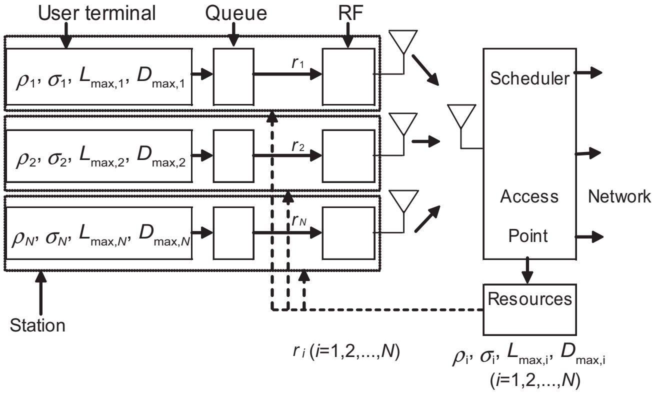

Fig. 2. Wireless network with our proposed scheduler

In this work, we perform all the simulations with one physical rate. However, in Sect.V we explain how it is easy to extend the proposed scheduler to run with different physical rate. Then, we provide below the necessary information to understand how IEEE 802.11 works with variable physical rate.

III. NEW SCHEDULER DESCRIPTION

Our proposed scheduler is based on a modified LR scheduler and the token bucket algorithm. Figure 2 illustrates a wireless network with our proposed scheduling algorithm.

Incoming traffic from session *i* (*i* = 1,...,*N*) passes through a token bucket admission control inside the user terminal and if $A_i(t)$ is the amount of session *i* flow that leaves the token bucket and enters the network in the time *t*, then $A_i(t)$ is bounded by the bucket size σ_i and bucket rate ρ_i (see Fig. 3). The token bucket for session *i* control arriving packets as follows. Upon arrival, a packet will be send out with the token bucket size decreased by the packet size in bytes provided there are enough tokens for the packet. Otherwise, the packet will be dropped. In our model, we consider for each packet some specific overhead of HCCA method. Then, the token bucket size will be decreased by the packet size and the overhead, which we will show below.

Application using session *i* declares the maximum packet size $L_{\max,i}$ and maximum required allowable delay $D_{\max,i}$ as well. Then the packet is queued in the station until it accesses the wireless medium and transmits. These parameters are used by the scheduler in the QAP to calculate the server rate for each session to guarantee the required delay and optimize the number of stations in the network.

Queueing delay is measured from when a packet is received and queued in the station until it accesses the wireless medium and transmits. This delay depends on the allocated server rate by the scheduler used in the network. For example, reference scheduler allocates server rate based on application mean rate. However, a VBR application has burst period with higher sending rate and some packets may be not transmitted in the current TXOP and both queue length and delay may increase.

In our scheduler, queueing delay depends on the token

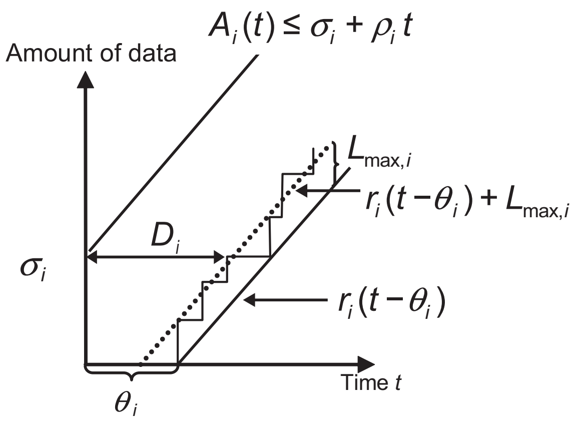

Fig. 3. Maximum delay D_i

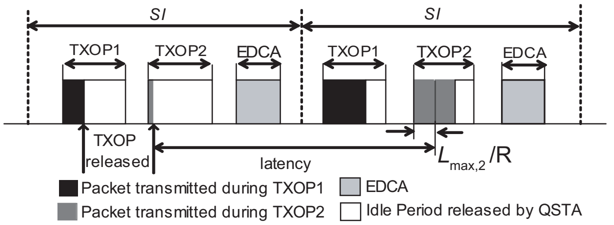

Fig. 4. Latency with new scheduler

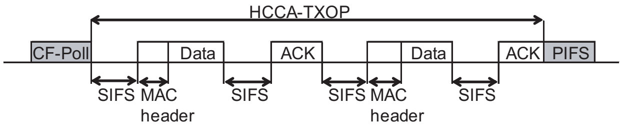

Fig. 5. Overhead for each TXOP

bucket parameters and the network latency. In [13] and [14], it is shown that if the input traffic $A_i(t)$ is shaped by

$$A_i(t) \le \sigma_i + \rho_i(t), \tag{4}$$

and the scheduler allocates a server rate r_i, then an LR scheduler can provide a maximum delay D_i bounded by

$$D_i \le \frac{\sigma_i}{r_i} + \theta_i - \frac{L_{\max,i}}{r_i}, \tag{5}$$

where r_i is the server rate, $L_{\max,i}$ is the maximum packet size, σ_i is the token bucket size and θ_i is the scheduler latency. Then, LR scheduler with token bucket provides a bounded delay because the traffic is bounded between two slopes depicted in Fig. 3 and estimated by (5). And the upper bound delay should be smaller or equal to the maximum required allowable delay:

$$\frac{\sigma_i}{r_i} + \theta_i - \frac{L_{\max,i}}{r_i} \le D_{\max,i}. \tag{6}$$

Our proposed scheduler modifies (5) to adapt to 802.11e wireless network depicted in Fig. 2. The latency of the scheduler may be seen as the worst-case delay. In the proposed scheduler, latency is an SI period and the time to transmit a maximum packet size (see Fig. 4). Our scheduler does not wait until the end of a TXOP to release the QSTA if there are no packets to be transmitted. This way, EDCA mechanism can transmit packets in this idle period of time and the network utilization increases. Figure 4 shows an SI with two TXOPs. In the first TXOP1 one packet is transmitted and then the station releases the TXOP sending a QoS Null frame to QAP because there are no more packets to be transmitted. When QAP receives a QoS Null frame, it can distribute the rest of the TXOP1 for EDCA scheme. In the first TXOP2, the station immediately releases the TXOP because there are no packets to be transmitted and the procedure is the same. The first packet arriving just after the released TXOP must wait for the next SI. Therefore, considering transmission delay for the first packet, the scheduler latency is

$$\theta_i = SI + \frac{L_{\max,i}}{R}, \tag{7}$$

where R is the outgoing link capacity. Now, it is necessary to consider the overhead for each packet that enters in the network. The overhead calculated for each packet should consider SIFS waiting time (twice), Ack packet length and MAC header length (see Fig. 5). The total overhead is

$$(2T_{\text{SIFS}})R + \text{ack\_size} + \text{mac\_header}. \tag{8}$$

Then the maximum packet size and token bucket size are adjusted to consider this overhead. In our scheme, when a packet passes through the token bucket, the removed token is equal to a packet length plus the overhead in (8).

And it is also necessary to consider one CF-Poll packet and one PIFS waiting time for each TXOP (see Fig. 5):

$$\Delta = T_{\text{CFPoll}} + T_{\text{PIFS}}. \tag{9}$$

Server rate to schedule a TXOP from session i is r_i. However, the total allocated server rate r'_i to schedule not only the TXOP, but also the overhead in (9) is $(r_i + \Delta R/SI)$. Then, from (5) and (7) to (9), the maximum delay with the new scheduler is bounded by

$$D_i \le \frac{(\sigma'_i - L'_{\max,i})SI}{r'_i SI - \Delta R + L'_{\max,i}} + SI + \frac{L'_{\max,i}}{R}, \tag{10}$$

where $L'_{\max,i}$ is the $L_{\max,i}$ with the overhead in (8) and σ'_i is the token bucket size with the same overhead. Due to space limitations, we omit the step to obtain (10).

And the delay constraint condition of the scheduler is

$$\frac{(\sigma'_i - L'_{\max,i})SI}{r'_i SI - \Delta R + L'_{\max,i}} + SI + \frac{L'_{\max,i}}{R} \le D_{\max,i}, \tag{11}$$

where physical rate, maximum packet size and token bucket size are parameters declared by the application. However, SI and total allocated server rate are parameters that must be calculated to satisfy (11). Equation (12) is the second constraint condition to calculate SI and server rate. The token bucket rate plus the rate to transmit the overhead (CF-Poll and PIFS) and a maximum packet size must be smaller than the server rate to bound delay. Then this second constraint condition is

$$\rho_i - r'_i + \frac{\Delta R + L'_{\max,i}}{SI} \leq 0. \qquad (12)$$

Reference scheduler does not provide any mechanism to estimate SI to bound delay or to maximize the number of stations, because each application requires an SI without any of these criterias to be used in (1) to calculate each TXOP. However, SI estimation is important because there is a tradeoff between a small and a large SI. Small SI reduces maximum delay, however overhead increases in the same time. On the other hand, for large SI, overhead decreases, but delay increases. Therefore, we need to calculate the optimal SI to allocate the maximum number of TXOP under these two above constraint conditions. The maximum number of TXOPs is achieved when the server rate for each station is the minimum to guarantee the delay bound. Then, we need to find the minimum for the following function:

$$f(SI) = \frac{\sum_{i=1}^{n} TXOP_i}{SI} \rightarrow \text{min}. \qquad (13)$$

Different optimization techniques can be used to solve this problem, for example, Sequential Quadratic Programming. Then with the optimal SI, we have the minimum server rate for each flow to bound delay and the TXOP for each flow can be calculated using (1) and (2) adjusted to our scheduled. Application rate λ is replaced by total allocated server rate r'_i calculated with our method and we should not consider Δ , then the new TXOP is

$$TXOP_i = \frac{r'_i SI}{R} - \Delta. \qquad (14)$$

SI and TXOP estimation are performed again if new stations wants to access QAP, stations leave the network or if same station changes its TSPEC requirements.

This analytical model considers only one physical rate. However, it is possible to extend this analyze to consider variable physical rate and we will explain how to do this in Sect.V.

IV. Performance Evaluation

Several simulation experiments have been carried out to evaluate the performance of the proposed scheduler and to validated the analytical model. The proposed scheme was implemented using ns-2 simulator [15] and our implementation is based on Stanford's NS-2 of EDCF/HCF [16]. In this paper, we only consider HCCA traffic, then if a QSTA wants to send a flow, it will use the HCCA. The HCCA duration limit is 490ms and the Beacon period is 500ms. The topology used in the simulation has one QAP and 18 nodes with only one traffic per node and the destination of all the flows is the QAP. In this topology, 6 QSTAs send CBR on-off audio traffic (64kb/s), 6 QSTAs send a CBR MPEG4 video traffic (3.2Mb/s) and 6 QSTAs send a VBR video traffic. Table I summarizes the different traffics used for this simulation. PHY and MAC parameters used in the simulations are summarized in Table II.

TABLE I

Description of the different traffics

Node	Application	Arrival Period (ms)	Packet size (max) (bytes)	Sending rate (kb/s) (mean)
1→6	Audio	4.7	160	64
7→12	VBR video	26	1024	≃200
13→18	MPEG4 Video	2	800	3200

TABLE II

PHY and MAC parameters

SIFS	16μs
DIFS	34μs
PIFS	25μs
CF-Poll	56 bytes
ACK size	14 bytes
PHY rate	36Mb/s
Minimum bandwidth	6Mb/s
Slot time	9μs
CCA time	4μs
MAC header	38 bytes
PLCP header length	4 bits
Preamble length	20 bits

Now, we compare the behavior of the reference HCF scheduler and the new scheduler. First, the token bucket parameters are estimated according to the input traffic characteristics and they are depicted in Table III. Note that the sender's traffic has to be known a priori. Given token bucket parameters, application can generate traffic to satisfy such parameters. In our simulations, however, we estimate token parameters to realize lossfree from given traffic. First, choose token bucket size and token bucket rate much larger than maximum packet size and mean application rate. After this, decrease the token bucket size until the token bucket start to drop packets. Then, decrease the token bucket rate until the token bucket start to drop packets. These are the minimum token bucket parameters because there are no dropped packets in the token bucket.

Then, the optimal SI is estimated according to the token bucket parameters, maximum required allowable delay, physical rate and maximum packet size length. Figure 6 shows the minimum for function (13) with different SIs. Value one means that TXOPs for all the stations (18) are allocated in exactly one SI and the maximum number of TXOPs that can be allocated is achieved when SI is 19ms for target delay of 40ms for each flow. With this optimal SI, all the stations are allocated in 0.81 SI and there is some idle SI, that can be allocated to EDCA scheme.

CBR MPEG4 traffic throughput is constant (3.2Mb/s) for both schedulers and to simplify curves and to compare the different schedulers, only one curve of VBR flow and audio

TABLE III

TOKEN BUCKET PARAMETERS

	Audio	VBR video	CBR MPEG4
Token Size(bits)	3000	18000	10000
Token Rate(kb/s)	64	500	4100

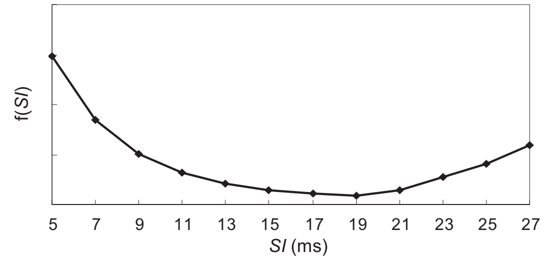

Fig. 6. Optimal SI

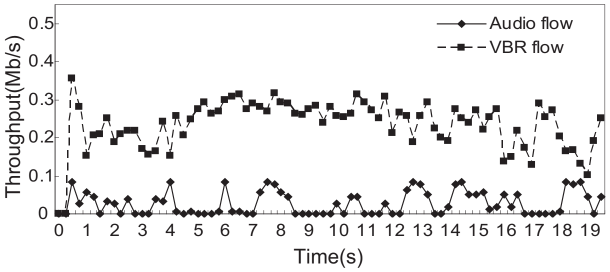

Fig. 7. Throughput versus time with reference scheduler

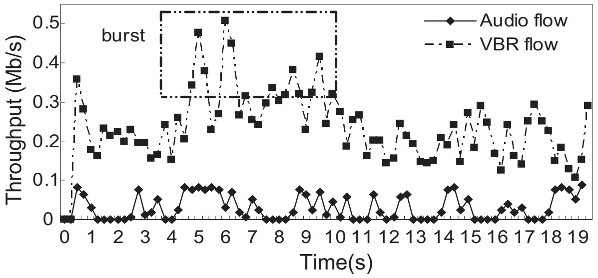

Fig. 8. Throughput versus time with new scheduler

TABLE IV

NUMBER OF DROPPED PACKETS

	Audio	VBR video	CBR MPEG4
Reference Scheduler	0	513	0
New Scheduler	0	0	0

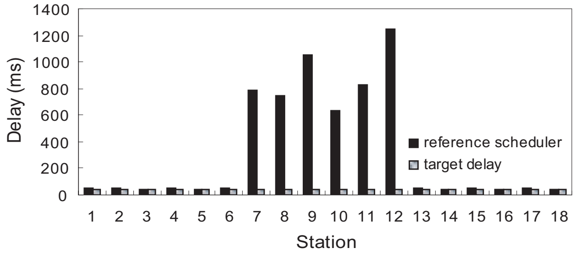

Fig. 9. Mean rate allocation : maximum delay for each flow with HCF reference scheduler

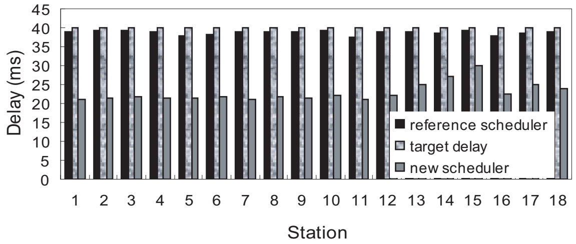

Fig. 10. Peak rate allocation : maximum delay for each flow with new scheduler and reference scheduler with different TSPEC (SI=40ms)

flow is shown on Figs. 7 and 8.

Curves on Figs. 7 and 8 show that the audio throughput is the same for both schedulers, because there are no burst in this traffic. For VBR flows, the reference scheduler allocates bandwidth to the station according to the mean application rate (200kb/s), then some packets are dropped and the delay requirement cannot be satisfied when the application rate is higher than 200kb/s, for example, in Fig. 8, there is a burst between 5s and 10s and peak rate is 500kb/s. And since the proposed scheduler allocates bandwidth to guarantee delay bound, all the packets are successfully delivered.

Table IV shows the number of dropped packets by the HCF scheduler and the proposed scheduler. Even as the queue size is 50 packets, reference HCF scheduler drops 513 VBR packets because the TXOP is estimated according to the mean application rate. However, VBR flow has a higher sending rate than the mean application rate (see Fig. 8) and it is not possible to transmit all packets during a TXOP. On the other hand, with the new scheduler, if token bucket allows the packets to enter in the queue, there are no dropped packets since allocated TXOPs to the different QSTAs are estimated to transmitt all the packets in the queue.

Figs. 9 and 10 represent the maximum delay for each station. For the proposed scheduler, all the flows have a maximum delay smaller than the target delay (40ms), because the server rate and the TXOP are calculated to bound delay. And the maximum delay of the VBR flows for reference HCF are uncontrolled because the queue lenghts are increasing during time (see Fig. 9). However, Fig. 10 shows that it is possible to guarantee delay with a different TSPEC for the reference scheduler if SI is equal to target delay and application peak rate is used instead of application mean rate. However, the maximum delay with new scheduler (around 20ms) is lower than the maximum delay with the reference scheduler (around 40ms).

In our scheduler, SI is estimated again if new stations enter(leave) the network or if some station requires a new TSPEC. Table V shows maximum required allowable delay

TABLE V

Maximum delay with different number of stations in the network and different maximum required allowable delay (CBR=40ms,VBR=60ms and Audio=50ms)

Simulation time(s)	SI (ms)	Number of stations	CBR Delay (ms)	VBR Delay (ms)	Audio Delay (ms)
0-5.5	18	CBR	18	-	-
5.5-10.5	19	CBR+VBR	21	23	-
10.5-15.5	21	VBR	-	41	-
15.5-20	23	VBR+Audio	-	38	38

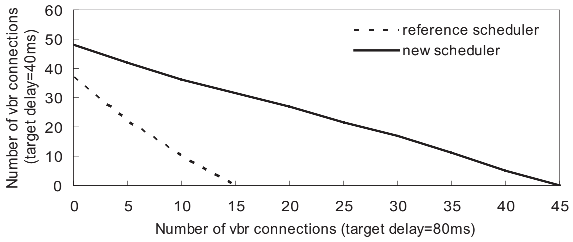

Fig. 11. Maximum number of connections with reference scheduler and new scheduler

when each station requires a different allowable delay. Our scheduler can bound delay in this situation as well, because SI estimation takes into account all allowable delays and SI will always be smaller than the minimum allowable delay.

Now, we compare the maximum number of connections with the new scheduler and the reference HCF scheduler with a TSPEC to guarantee delay. Figure 11 shows the number of connections for both schedulers with VBR traffic for different target delay (40ms and 80ms). The new scheduler is able to allocate larger number of connections than the reference scheduler, because SI is calculated to optimize the network utilization (see Fig. 6). For example, when the target delay is 80ms, SI for the reference scheduler is 80ms. However, with the new scheduler, SI is 42ms. Thus, for this target delay, it is possible to allocate 43 stations with the new scheduler and only 13 stations with the reference scheduler.

V. Conclusion and Future Work

We have designed and evaluated a new MAC scheduling algorithm for IEEE 802.11e wireless network with the aim to guarantee a bounded delay for different types of flows with QoS requirements with bandwidth optimization. First, we have developed an analytical model to calculate the optimal SI, server rate and TXOP to bound delay and to allocate the maximum number of stations. Several simulations were carried out to evaluate the performance of the system and we explained that it is easy to extend this new scheduler to consider variable transmission rates. The results show that the new scheduler succeeds on to guarantee a bounded delay and to maximize the number of stations in the wireless network.

Now, we show how the new scheduler can be easily extended to multi-rate scheme. We are not interested in the link adaptation algorithm itself, but how the new scheduler can be used to support multiple transmission rates. Then, we assume that we know the physical rate from one of the link adaptation algorithm and this physical rate will be used in (11), (12) and (14) to calculate TXOP and server rate to bound delay. When the stations move away from the QAP, it decreases its transmission rate used for the transmissions from 54Mbps (maximum) to 6Mbps (minimum) in IEEE 802.11a. With 6Mbps of physical rate, TXOP will be larger than with 54Mbps of physical rate. Then, the reference admission control (3) admits stations to enter in the network based on the minimum physical rate to guarantee the delay required by the application.

In our future research, we will analyze the IEEE 802.11e performance with variable transmission rate, because wireless channel condition dynamically change over time and space and the transmission rate is chosen in an adaptive manner by, for example, an auto rate control algorithm. We have explained that it is easy to extend this new scheduler to consider variable transmission rates. However, we should consider the effect on QoS parameters, for example packet loss and delay bound.

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