An Efficient QoS-based Uplink Scheduling Scheme for IEEE 802.16e Mobile Stations

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***Abstract*—The IEEE 802.16e-2005 standard for broadband wireless access provides a rich quality of service (QoS) framework suitable for supporting a multitude of services. In IEEE 802.16e, the uplink resource allocation is based on a request-grant mechanism where a mobile stations (MS) requests allocations of transmission opportunities from the base station (BS). Every frame, the BS decides the amount of resources to be granted for each uplink connection according to its QoS parameters. While the grant is decided on a connection basis, the BS aggregates the grants allocated for all connections of each MS and adds a single entry for each MS in the allocation MAP message. Two main challenges exist for scheduling at the MS side: the first is how to divide the grant among the connections according to their declared QoS parameters and requested bandwidth and the second is to be able to perform this operation prior to the arrival of the subsequent allocation from the BS. In this paper, we describe a new efficient scheme for mobile station uplink scheduling that meets these challenges. The scheme is a hierarchical credit-based algorithm based on the deficit round robin method. The algorithm is designed to prevent bandwidth stealing and starvation of low-priority connections. We provide simulation results that show the excellent performance of the scheme even under extreme overload conditions. The results show the isolation of service classes and the stability of the scheme.**

Keywords- IEEE 802.16e; uplink scheduling; quality of service; deficit round-robin

I. INTRODUCTION

The IEEE 802.16e [1-3] layer 2 defines a connection-oriented packet based protocol. All transport connections must be established in advance between the base station (BS) and mobile station (MS). The service is based on a polling-based centralized media-access and resource management scheme where all resources are centrally managed by the BS. The BS has complete information about the currently served MS's and their established connections.

The uplink medium access is based on a request/grant mechanism, where a MS requests bandwidth from the base station (BS). The BS performs scheduling among the contending MS's connections and grants bandwidth to meet the connections' QoS parameters. The downlink access is based on broadcast media-access. The BS has the full responsibility for forming the downlink burst and filling it with the packets destined for the various MS's.

The BS transmits a broadcast message uplink MAP (UL-MAP) in every frame to announce the uplink scheduled allocations. In order to minimize the overhead of the UL-MAP message, the resources allocated for all connections of the scheduled MS's are aggregated and added as a single entry in the UL-MAP message.

In this paper, we focus on one of the important aspects of the IEEE 802.16e standard, namely, the scheduling performance at the mobile stations. We consider the scheduling problem from two aspects. The first is complying with the 802.16e functional requirements of satisfying connection demands according to the negotiated QoS parameters of each connection. The problem is important since the BS aggregates the grants allocated for all connections of each MS and add a single entry for each MS in the allocation MAP message and therefore each MS has to decide how to allocate the grant among the connections. The second is to implement an efficient algorithm that meets the real-time constraints when implemented on typical mobile station hardware platforms.

The rest of this paper is organized as follows. In section II. We provide a survey on related work. Section III highlights problem motivation and gives details about the proposed uplink scheduling scheme. Results showing the performance of the proposed scheme are presented in section IV. Section V concludes the paper.

II. RELATED WORK

The problem of downlink scheduling in IEEE 802.16 scheduling has been studied extensively. In this section we focus on related work in the area of MS uplink scheduling and schemes for BS uplink/downlink scheduling which we judge as related to the proposed MS uplink scheduling scheme. MS uplink scheduling carries a lot of resemblance with BS downlink scheduling. The majority of previous work for BS downlink/uplink scheduling and MS uplink scheduling has been based on round-robin (RR), weighted round-robin (WRR), deficit-round-robin (DRR), weighted-fair queueing (WFQ), proportional fair (PF), and Earliest-deadline-first (EDF) scheduling. Hierarchical scheduling using a combination of these methods to serve multiple classes has also been reported.

Kwon et al. [4] propose using channel quality indications as supported in IEEE 802.16e to implement a cross-layer BS utility based scheduling scheme which can be tailored to account for connections rates and QoS requirements. The paper compares uplink and downlink performance for RR and PF scheduling along with band adaptive modulation and coding (AMC) mode.

Cicconetti et al. [5] consider downlink/uplink scheduling at the BS. They propose using DRR for the downlink scheduling because of its low complexity whereas WRR is used for BS uplink scheduling.

While the work by Sayenko et al. [6] focuses mainly on BS downlink scheduling, the proposal is very relevant to our work. The proposed BS downlink scheduling scheme is based on the WRR method. The scheme defines a slot as the basic allocation unit which is a sub-channel and symbol in a specific frame. The number of slots, which the BS has to allocate for each connection based on its QoS requirements, is the weight value of the WRR scheduler. The scheme is based on three steps 1) Allocation of the minimum number of slots to ensure the basic QoS requirements; 2) Allocation of unused slots such that each connection gets the minimum of the maximum it can request and what has been allocated to it and the amount it would get if each connection is allocated equal share of the remaining slots; 3) Ordering of the slots where the BS has to select the order of slots to improve the provisioning of the QoS guarantees. We use similar ideas to steps 1 and 2 in our proposed scheme.

The work by Settembre et al. [7] propose schedulers for BS downlink/uplink scheduling and MS uplink scheduling. The scheme is a hierarchical scheduler with fixed allocation to unsolicited grant service (UGS) traffic. For real-time polling service (rtPS) and non-real-time polling service (nrtPS) connections, the scheme first serves each connection with the minimum of its minimum reserved rate and requested bandwidth. Any leftover grant is allocated using WRR. Best effort (BE) connections are served using RR. The shortcomings of the proposed scheme are mainly the high overhead associated with the various rounds associated with RR and non-uniform treatment of connections from the different classes. One of the advantages of our proposed scheme is that rtPS, nrtPS, and BE connections are handled identically.

Rath et al. [8] consider BS uplink scheduling based on DRR. The main focus is on obtaining an optimal polling interval at which the BS should poll the subscriber stations to ensure that the delay requirements of traffic are met with bounded unfairness in bandwidth allocation. A scheme based on opportunistic deficit round-robin (O-DRR) is devised to schedule sessions by taking into account the variations in the wireless channel and demonstrate that there exists a range of values of the polling interval over which the proposed scheduler is fair.

III. THE PROPOSED MOBILE STATION UPLINK SCHEDULING SCHEME

A. Problem Definition and Motivation

The main challenge in the MS uplink scheduling stems from the fact that while the MS sends a Bandwidth Request (BWR) on a per-connection basis, the BS does not allocate the grant on a per-connection basis. Every frame, the BS decides the amount of resources to be granted for each uplink connection according to its QoS parameters. The BS aggregates the grants allocated for all connections of each MS and adds a single entry for each MS in the UL-MAP message. It is the responsibility of the MS to distribute this allocated grant among its connections. In case of overloading conditions, the BS may not grant the needed resources for all connections. Hence, an uplink scheduler should be implemented at the MS side to share the limited grant allocated by the BS between different connections according to the negotiated QoS parameters of each connection. The allocation at the MS could simply be based on strict priority or variants of round-robin scheduling. However, such simplified treatment would result in violation of the QoS parameters of the connection or starvation of low priority connections, for example, in overload conditions.

We explain the potential problem of naïve allocation of the grant among the connections using an illustrative example. Assume an MS which has three connections (1, 2, 3) one of each of the service classes rtPS, nrtPS, and BE respectively. At some frame n, the MS requests an allocation of b_1, b_2, and b_3 bytes for three connections (1, 2, 3) respectively, where $\sum_{j=1}^{3} b_j = B$. The request arrives at the BS which receives other requests from other MS's for a total bandwidth of W which is larger than the amount available on the uplink. The BS uplink scheduler would not be able fulfill the total requests and allocates $B' < B$ to the MS. Assume further that at frame $n+2$ when the MS is supposed to use this allocation, the amount of backlog in the queues for connections 1 through 3 has increased to become b_1', b_2', and b_3' respectively. In this scenario, $\sum_{j=1}^{3} b_j'$ shall be greater than B', and thus a scheme that uses strict priority (SP) or round-robin (RR) could allocate the overall grant to the first served connection (for example if $b_1' > B'$ and first connection is served first). The proposed scheme in this paper would avoid such problem. It also avoids uncontrolled bandwidth stealing/unfair allocation, starvation of low priority connections, and excessive fragmentation as will be discussed below.

B. Steps of the Scheduling Scheme

The proposed IEEE 802.16e MS uplink scheduling scheme can be classified as a hierarchical credit-based mechanism. The proposed scheme is simple and scalable. It achieves the following objectives:

- Support for five classes of connections (UGS, ertPS, rtPS, nrtPS, BE) in addition to management traffic.
- Isolation of all classes under normal and overload conditions.
- Prevention of high-priority traffic from stealing bandwidth of other traffic. All connections are provided with the amount of bandwidth they requested. Excess bandwidth is divided among connection according to their priority.

– Prevention of starvation for best effort traffic.

As explained in section III.A, when the received grant is inconsistent from the requests, then a simplified scheme that allocates bandwidth in say strict-priority manner could cause unfairness and violation of the expected service quality of the connections.

The proposed scheduling scheme is a hierarchical scheme treating UGS and ertPS connections differently from rtPS, nrtPS, and BE connections. It finishes its work in a maximum of three rounds thus resulting in a highly efficient implementation (note that schemes such as RR and DRR can suffer from a large number of rounds depending on grant size and number of connection).

Since the scheme is credit-based, we describe first how the connections credits are calculated. We maintain the following parameters per connection:

– N_1: A configurable parameter that is used to calculate the amount of credit allocated per connection. The unit of this parameter is frames.

– N_2: A configurable parameter used to calculate the maximum possible value of a connection's credit. The unit of this parameter is frames. This parameter may be a function of the time base QoS parameter. Typically, $N_2 > N_1$.

The following constants/variables are maintained on a per-connection basis for rtPS, nrtPS, and BE connections:

Periodic Credit (PC): this is a constant that defines the virtual credit that should be assigned to each connection every *N1* frames. This periodic is calculated in bytes as:

$$PC = \text{Minimum Reserved Traffic Rate} \times \text{Frame Duration} \times N_1$$

Maximum Credit (MC): this is a constant that defines an upper limit on the maximum virtual credit the connection may have at any time. This maximum credit is calculated in bytes as:

$$MC = \text{Minimum Reserved Traffic Rate} \times \text{Frame Duration} \times N_2$$

Current Credit (CC): this is a variable that holds the current amount of credit allowed for the connection in bytes. It is initialized with the value of the connection's periodic credit. The update of the value of this variable is described below.

Requested Bandwidth: this is a variable that holds the amount of pending bandwidth requested from the BS in bytes. By pending we mean "not yet granted".

The value of *Current Credit* is updated as follows:

– Upon receiving grant and before connection serving, the credit shall be updated only if the connection queue is not empty and there is still remaining grant to serve the connection. We set:
$$CC = \min(CC + \Delta n / N_1 \times PC, MC)$$
where Δn is the number of frames since that last credit update.

– Upon serving packets from the connection queue, the value is updated as follows:
$$CC = \max(0, CC - \text{served packet size in bytes}).$$

The proposed scheduler starts with serving UGS connections in a SP manner. As the maximum sustained traffic rate is the same as the minimum reserved traffic rate for UGS connections, it is guaranteed that the BS shall allocate grant for all of the pending traffic of UGS connections. After serving UGS connection, the scheduler proceeds to serve ertPS connections in a similar manner.

The scheduler works in three rounds to serve the rtPS, nrtPS and BE connections. In each round, the scheduler scans the connections starting from the connection with highest serving priority to the lowest serving priority. The serving priority is determined as described in section III.C. In the first round, each connection is served up to the minimum of its requested bandwidth and current credit. The purpose of the first round is to satisfy each connection minimum reserved traffic rate. The following round will insure no connection is served more than its requested grant.

If there is remaining grant from the first round, the scheduler starts a second round. In the second round, each connection is served up to its requested bandwidth that has not been granted in the first round. The second round typically consumes the entire available grant. The restriction of limiting the allocated grant of a connection to the amount of requested bandwidth will prevent connections with high serving priority from stealing bandwidth requested previously by the lower priority connections.

If there is remaining grant after the second round, the scheduler proceeds to the third round, in which connections will be served up to whatever grant is available to serve the waiting traffic in the connection queues. The overall scheme is depicted in Figure 1.

C. Assigning the Connections' Serving Priority

The algorithm scans the connections in order of priority form highest to lowest. The priorities are assigned as function of the connection class and the connection parameters. The following method is followed for assigning priorities to the connections:

UGS/ ertPS connections are assigned static serving priority according to the following order: scheduling type (UGS has higher priority than ertPS), maximum latency, tolerated jitter, and traffic priority. Therefore, all UGS connections have higher priority than ertPS connections. Within the same class, the connection with smallest maximum latency will have higher priority. If two connections have the same maximum latency, the connection with less tolerated jitter shall be assigned higher serving priority. If two connections have the same maximum latency and the same tolerated jitter, the connection with higher traffic priority QoS parameter, shall be assigned higher serving priority.

rtPS, nrtPS and BE connections are assigned static serving priority according to the following order: maximum latency, tolerated jitter, scheduling type (rtPS has the highest priority followed by nrtPS and finally BE), and traffic priority. According to the IEEE 802.16 standard, the traffic priority is the least significant QoS parameter to differentiate between connections. While maximum latency and tolerated jitter are typically not specified for nrtPS and BE, in our implementation we assign these parameters large default values in order to treat the rtPS, nrtPS and BE connections in an identical manner.

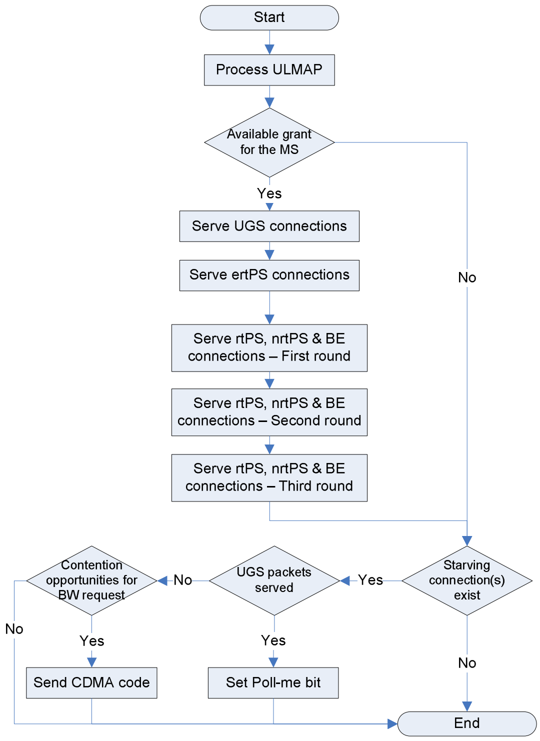

Figure 1. The overall scheduling scheme

IV. PERFORMANCE EVALUATION OF THE PROPOSED UPLINK SCHEDULING SCHEME

In this section we report results showing the performance of the proposed uplink scheduling scheme. We use discrete-event simulation to verify the scheduling algorithm performance. All packets are generated in accordance with a Poisson process whose rate specified in the experiment parameters shown in table 1 and table 2. This is true for all types except for UGS in which case, the packets are generated with a constant rate. The purpose of the simulation is to show the possibility of isolating traffic classes without impacting the low priority traffic. The system collects statistics on a per-connection basis such as the average delay in the queues, the average and distribution of the number of packets in the queue, the number of dropped packets due to a full buffer at the connection queue, the dropped packets due to policing, and the dropped packets due to expiration. Each simulation run is executed for a sufficiently large number of frames which in the shown results is taken as 100,000 frames.

We perform two experiments each including four connections of different types: UGS, rtPS, nrtPS, and BE. The MS is provisioned for a maximum uplink capacity of 3 Mbps. In the first experiment, the UGS, rtPS and nrtPS connection rates are fixed while the BE connection rate is varied. The purpose of the experiment is to show that with increasing BE traffic rates, other connections performance is hardly affected. In the second experiment, we maintain a fixed input bit rate for the UGS, nrtPS and BE connections while varying the rtPS connection rate. The purpose of this experiment is to show that even when a high-priority traffic connection rate is increased, other connections performance is not affected even for BE traffic until the incoming traffic rate exceeds the overall provisioned capacity.

A. *First Experiment*

In the first experiment, the parameters of the four connections are as shown in table 1. We report the following performance metrics obtained as the BE connection rate is increased (the minimum reserved rate is fixed): average delay for each of the connections and the dropping rates (the overall dropping due to expiry, full buffers, and policing), in each connection. The overall BE rate is varied from 62 packets/sec to 1062 packets/sec resulting in an uplink subscription ratio in the range of 50% to 130%.

Figure 1a shows the results of the average delay received by the four connections. We notice here that regardless of the overall load, the UGS, rtPS and nrtPS connections delays are not affected. The BE connection delay starts to increase when the incoming traffic exceeds 3 Mbps. Figure 1b also shows that the dropping percentage in the BE SDU traffic starts to increase as the BE load increases. No drops in the UGS are encountered. For the rtPS and nrtPS connections, very low drops due to expiry and policing are observed.

B. *Second Experiment*

The parameters of the four connections are shown in Table 3. We report the same performance metrics reported in the first experiment as both the rtPS connection rate and its minimum reserved traffic rate are increased. The connection rates are selected to vary the link subscription ratio from 40% to 130%. We expect that all connections have their minimum rate met until the link utilization approaches 100% (i.e. overload condition).

Figure 2.a shows the average delay for each of the connections. The rtPS connection performance remains consistent for all utilization levels. However, by inspecting Figure 2b we can see that when the incoming rate increases above 3 Mbps, rtPS traffic starts to be dropped which occurs mainly due to expirations. The nrtPS and BE connections have good performance. The delays are constant until the overall incoming rate increases above 3.15 Mbps where the delays increase. In Figure 2b, we observe that BE packet dropping for all incoming rates is between 0.2 and 1.9%. When rtPS rate increases above its maximum sustained traffic rate, policing starts to limit the rtPS rate and the delay performance remains predictable.

Intuitively, a scheme that does not isolate classes as proposed here will degrade BE traffic performance due to allocation of its grant to other high priority connections even if those connections are exceeding their contracted/declared rates.

TABLE I. FIRST EXPERIMENT - PARAMETERS OF THE FOUR CONNECTIONS

	Queue size (Pkts)	Packet Rate (Pkt/sec)	Packet Length (bytes)	Max latency (ms)	Min reserved rate (bps)	Max sustained rate (bps)
UGS	200	292	uniform(93, 93)	20	148,800	148,800
rtPS	200	1171	uniform(55, 73)	20	512,000	600,000
nrtPS	200	500	uniform(80, 220)	300	512,000	600,000
BE	200	62 to 1062	uniform(100, 500)	5,000	1,200	1,660,000

TABLE II. SECOND EXPERIMENT - PARAMETERS OF THE FOUR CONNECTIONS

	Queue size (Pkts)	Packet Rate (Pkt/sec)	Packet Length (bytes)	Max latency (ms)	Min reserved rate (bps)	Max sustained rate (bps)
UGS	200	200	uniform(93, 93)	20	148,800	148,800
rtPS	200	293 to 5566	uniform(55, 73)	20	150,000 to 1,950,000	2,250,000
nrtPS	200	500	uniform(80, 220)	300	512,000	600,000
BE	200	125	uniform(100, 500)	5,000	1,200	300,000

The scheme has been implemented on a target platform with ARM9 processor running at 192 MHz. Even in very high load, the execution time for the scheduling in a frame does not exceed 3.5 msec which indicates suitability for implementation of the algorithm in real-time. Detailed results are omitted due to space limitations.

As can be seen, the results obtained from the two experiments prove the excellent fairness and the capability to meet the contracted QoS parameters of the different classes.

V. CONCLUSIONS

The paper proposed and evaluated the performance of an uplink scheduling scheme for IEEE 802.16e based mobile stations. The scheme is a hierarchical scheduling scheme that has two broad classes: the UGS/ ertPS class and rtPS/nrtPS/BE class. The UGS/ertPS class is served using static priority. The rtPS/nrtPS/BE class is a three-round credit-based scheme based on WDRR. Credit calculation and priority assignment have been fully defined and are linked to connection serving class and QoS parameters. The scheme has been designed to achieve two broad goals. The first goal is to meet the IEEE 802.16e functional requirements and the second goal is to meet the real-time constraints of implementation in a resource-constrained CPU suitable for mobile station and handsets. The functional requirement is defined as the sharing the allocated grant from the BS among different connections in a fair manner according to each connection QoS parameters mainly rates, delay and jitter. The real-time constraint is to perform scheduling and prepare the PDU's to transmit in the limited interval between receiving the UL-MAP and the scheduled transmission time. Experimental results demonstrate that the proposed scheme meets both the functional requirements and the real-time constraints even in extreme overload conditions.

Future extensions should include comparisons with other schemes proposed in the literature and optimizing the packing and fragmentation processing along with the scheduling. We shall study doing fragmentation in the first two rounds instead of only the third round. Another important aspect is to allocate the grant in a manner that depends on the adaptive coding/modulation applied in order to meet certain bit-error-rate requirements for the connections.

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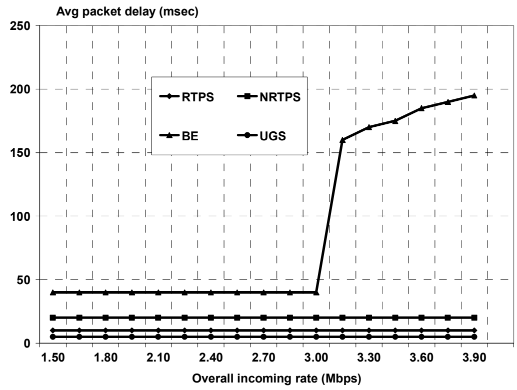
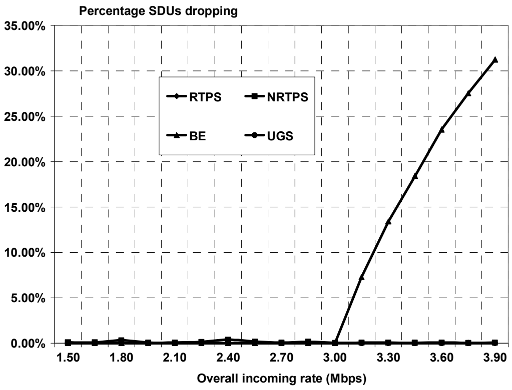
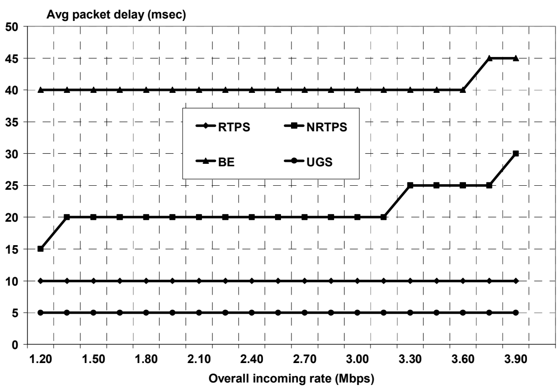


(a)



(b)

Figure 2. First Experiment: (a) Average delay and (b) SDU dropping rate for the UGS, rtPS, nrtPS, and BE connection



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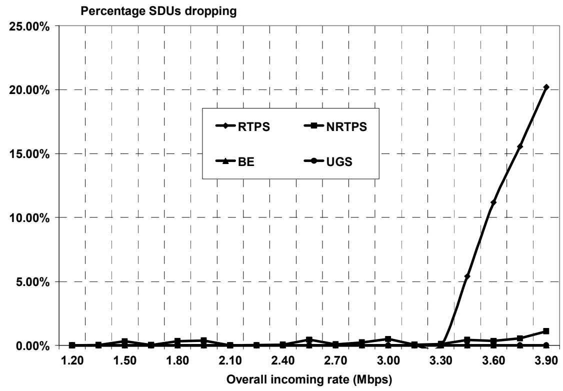

(b)

Figure 3. Second Experiment: (a) Average delay and (b) SDU dropping rate for the UGS, rtPS, nrtPS, and BE connection