An Opportunistic Uplink Scheduling Scheme to Achieve Bandwidth Fairness and Delay for Multiclass Traffic in Wi-Max (IEEE 802.16) Broadband Wireless Networks

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Abstract— **We present a novel scheme for uplink scheduling in WiMax networks that attempts to balance worst-case fairness in bandwidth allocation with the delay requirements of multiclass traffic, while taking the varying nature of the wireless channel into account. We assume a polling mode of operation at the base station (BS), and provide an analytical technique for obtaining an optimal polling interval k at which the BS should poll the subscriber stations (SSs) to ensure that the delay requirements of traffic are met, while the relative unfairness in bandwidth allocation remains bounded. We also devise an *opportunistic deficit round robin (O-DRR)* scheme that schedules sessions by taking into account the variations in the wireless channel and the delay constraints of multiclass traffic. We demonstrate that our scheduler provides fairness in bandwidth allocation and robust delay guarantees, thus giving a provider a choice of balancing fairness with delay.**

Fig. 1.   Frame Structure in IEEE 802.16

I. INTRODUCTION

The WiMax standard [1], [2], [3], in its simplest form, specifies a time-division duplex (TDD) system that provides access to each subscriber station (SS)/user using demand assignment multiple-access time-division multiple access (DAMA-TDMA). DAMA is a capacity assignment technique that adapts to the demands of multiple users by dynamically assigning time slots to users depending on their bandwidth and QoS requirements.

In WiMax, time is divided into frames, each of which, in turn, is composed of a fixed number of slots [4], [5], [6]. Each frame consists of an *uplink subframe* and a *downlink subframe* (cf. Fig. 1). Bandwidth-requests are normally transmitted in two modes: a *contention mode* and a *contention-free mode* (polling). In the contention mode, the SSs send bandwidth-requests during a contention period in control slots in the uplink subframe. Grants from the BS are communicated to SSs during control slots in the downlink subframe. Contention is resolved by the BS using an exponential back-off strategy, and the grants thus communicated are used to schedule data either in the uplink subframe corresponding to the ongoing frame or the next one.

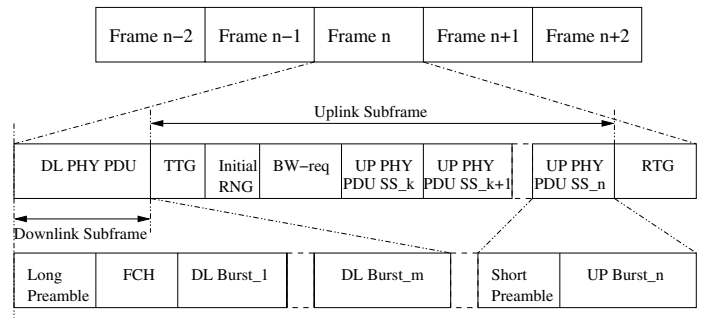In the contention-free mode, the BS polls each SS, and an SS in reply sends its bandwidth-request. The polling interval must be such that the delay requirements of the various classes of traffic/services can be met.

While the WiMax standard specifies the request-grant mechanisms and the service types [2], [4] it leaves open the scheduling mechanism to be used, thus allowing for providers and vendors to innovate in this area. Towards this end, we suggest a polling-based opportunistic deficit round robin (O-DRR) scheduling scheme for the uplink flows that is unique, in that it attempts to balance the worst-case unfairness in bandwidth allocation with the delay requirements of multiclass traffic, while taking the varying nature of the wireless channel into account.

To achieve this, in the polling mode of operation, we first obtain a polling interval k at which subscribers for each class of traffic must be polled so that the twin objectives of meeting the delay requirements and being fair in bandwidth allocation may be achieved. Having obtained this interval, we devise a scheduling strategy that meets the QoS objectives.

We provide an analytical technique for obtaining the polling interval k, which minimizes a measure of the worst-case unfairness plus normalized delay. We also propose the O-DRR algorithm, which we demonstrate provides fairness in bandwidth allocation and robust delay guarantees. Our algorithm addresses the more complex problem of uplink scheduling, requires no fluid-flow simulation in the background and makes

no assumptions about the queue sizes at the SS's being known at the BS.

The rest of the paper is organized as follows. In Section II we give an operational overview of our O-DRR scheme. In Section III, we explain the optimization technique used to find the polling interval for uplink scheduling for a given class of traffic, and provide a closed-form expression for the optimal polling interval. In Section IV, we explain our bandwidth assignment technique, which incorporates in the scheduling process both the channel condition between the BS and SS and the delay guarantees required by different classes of traffic. In Section V, we discuss our simulation models and experiments, while in Section VI, we present some concluding remarks.

II. OPERATIONAL OVERVIEW

Our scheme works by obtaining a list of *schedulable users*, based on the traffic requirements of the users and the signal-to-interference-plus-noise ratio (SINR) of the wireless channel. Polling is performed by the BS, only once every k frames, which we term a *scheduling epoch*. That is, once every k frames the BS determines the set of SSs that are *eligible* to transmit, and their bandwidth requirements. We label these SSs the *eligible set*. An SS is eligible if, at the polling instant, it has a non-empty queue and the SINR of its wireless link to the BS is above a minimum threshold (say, $SINR_{th}$). We observe here that the SINR of a wireless link between a SS and a BS is obtainable in the IEEE 802.16-standard, during each frame, from measurements made at the physical layer.

Once determined, the membership of the eligible set is frozen for the entire scheduling epoch. We also define a *schedulable SS* to be one that is eligible during a given frame of a scheduling epoch and that was eligible at the start of that epoch. During a scheduling epoch, therefore, the BS only schedules traffic from the schedulable set. (That is, the BS does not discover the status of the queue and wireless link of the remaining SSs in the network until its next polling opportunity.)

For each subsequent frame in the scheduling epoch (that is, for every frame for the next k frames), the BS schedules, using Opportunistic Deficit Round Robin (to be described shortly), the transmissions of the *schedulable SS*'s. Note that the membership of the schedulable set *changes dynamically* from frame to frame during a scheduling epoch, depending on the state of the channel between the SS and the BS. At the end of k frames, the BS recomputes the states of all of the SSs (by polling), and begins the above process over again.

We determine the best choice of the polling interval k by considering the maximum delay that a set of SSs can tolerate and the worst-case relative fairness in their bandwidth allocations. That is, our goal is to ensure that we choose a k such that every session is polled within a time kT_f (where T_f is the duration of a frame) that is less than its delay tolerance T_d, while still being fair to the different sessions. Since T_d is different for different classes of traffic (e.g., 50msec for rtPS traffic, 200msec for nrtPS traffic and 500msec for BE traffic),

the BS must poll in a manner that all of the above delay requirements are maintained.

An analysis for single-class case was presented in a previous work [7]. So, we will focus here on the multiclass case.

III. DETERMINING THE OPTIMAL POLLING INTERVAL k

As explained earlier, the BS needs to poll the SSs to discover the bandwidth and QoS requirements of the SSs. It is crucial to find an appropriate value for k, such that both efficiency and fairness are balanced. Our proposal is to minimize a combination of the worst-case relative fairness in bandwidth plus the normalized delay, where the provider may choose the relative weightage of the two quantities.

We denote the duration in slots of the downlink and uplink subframes by T_{dl} and T_{ul} respectively, so that the frame duration $T_f = T_{ul} + T_{dl}$ slots.

In our scheme, the BS maintains a list L of all SSs. We denote by ϕ_i the ideal share of bandwidth to be obtained by SS_i. Slots in the uplink subframe T_{ul} are divided proportionately among the SSs in the ratio of their ϕ_i's. The BS polls the SSs to discover their bandwidth requirements and updates an active list L_{active} of SSs, with the polling repeated at the start of every scheduling epoch.

Although polling is done once at the start of each scheduling epoch, scheduling itself is performed in each frame, based on the opportunity condition $SINR_i \geq SINR_{th}$, where $SINR_i$ is the SINR of the channel between the BS and SS_i. Hence, polling is done once every kT_f slots, whereas scheduling is done T_f slots. Therefore, if a packet/data at an SS misses one round of polling, it will require at least $(k+1)T_f$ time slots to be transmitted.

We let i and j be a pair of SSs that are continuously backlogged during an interval (t_1, t_2). The *fairness measure* $FM(t_1, t_2)$ over all pairs of flows/SSs i and j that are backlogged in interval (t_1, t_2) is then defined as [8]:

$$FM(t_1, t_2) = \left(\frac{sent_i(t_1, t_2)}{\phi_i} - \frac{sent_j(t_1, t_2)}{\phi_j} \right), \quad (1)$$

where $sent_i(t_1, t_2)$ and $sent_j(t_1, t_2)$ represent the amount of traffic sent by the backlogged flows i and j, respectively, and ϕ_i and ϕ_j represent the bandwidth share of flows i and j, respectively.

If the share of all SSs is equal (when all are backlogged), $\phi_i = \phi_j = 1$, and $\sum_i \phi_i = N$, where N is the total number of SSs in the system. As discussed in [8], if Q_i is the quantum of slots for SS_i in each round of a DRR scheme, then we define:

$$\phi_i = \frac{Q_i}{Q}, \quad \text{where} \quad Q = \min_i \{Q_i\} = \frac{T_f}{N}. \quad (2)$$

The worst-case occurs when only one SS (say SS_i) is backlogged at the instant of polling by the BS, but each of the $N-1$ remaining SS's becomes backlogged *immediately* thereafter. Hence, $Q_i = T_f$ and $\phi_i = N$. In this case, the

worst-case fairness measure $|FM_{wc}(t_1, t_2)|$[1] can be expressed as:

$$|FM_{wc}(t_1, t_2)| = \left(\frac{R(t_2 - t_1)}{N} \right). \qquad (3)$$

The worst-case time interval for our system occurs when $(t_2 - t_1) = kT_f$. Note that each frame consists of both uplink and the downlink slots, while only the uplink slots are used for SS to BS transmission. Assuming that the uplink and downlink sub-frames occupy an equal number of slots, and that there is no wastage of slots (i.e., the administrative slots are negligible, so that all the slots in the uplink can be assigned to traffic), the usable slots in $(t_2 - t_1)$ are αkT_f, where α is a system parameter between 0 and 1. We assume $\alpha = \frac{1}{2}$, henceforth. So, the worst-case fairness measure is:

$$|FM_{wc}(t_1, t_2)| = |FM_{wc}(kT_f)| = \left(\frac{\alpha RkT_f}{N} \right), \qquad (4)$$

where R is the maximum data rate achievable, which, per the IEEE 802.16 standard, is 120 Mbps for a 64-QAM modulation scheme. Our aim is to find a k such that the BS can poll the SSs to achieve the smallest worst-case fairness measure FM_{wc} and minimum delay. For this, we define a normalized delay (ND) as: $ND = \frac{T_d}{kT_f}$, where T_d is the delay bound of traffic at a SS (the maximum delay that a flow for a particular application can tolerate, e.g., 10 msec, 50 msec, 200 msec and 500 msec for UGS, rtPS, nrtPS and BE services, respectively). We would like the optimal k in our solution to be such that the worst-case fairness measure and normalized delay are minimum. This can be achieved by the following optimization framework.

$$\min_k f(k) = c_1 |FM_{wc}(k)| + c_2 ND(k), \qquad (5)$$

where c_1 is the cost for a unit of FM per bit and c_2 is the cost per normalized delay. The worst-case value of k can be found at the equilibrium point, where, $c_1 |FM'_{wc}(k)| = -c_2 ND'(k)$, which simplifies to,

$$k = \sqrt{\left(\frac{c_2}{c_1} \frac{NT_d}{R\alpha T_f^2} \right)} = \sqrt{\left(c \frac{NT_d}{R\alpha T_f^2} \right)}, \qquad (6)$$

where c is the ratio of the cost per unit delay to the cost per unit FM. Thus, our method computes a different k for each traffic type. If there is a mix of traffic and T_ds are different for different classes of traffic, then the BS can either poll the SSs with different ks, i.e., poll one set of users at k_1 and another set at k_2, or poll all users with the minimum k. We use the lowest k, i.e., the k for the minimum T_d, to poll all users, and modify our O-DRR scheduling algorithm such that the users with looser delay requirements do not get resources at the expense of users with tighter delay requirements.

Having obtained the optimum k for single-class traffic or the minimum k for multiclass traffic, we perform uplink bandwidth assignments using our O-DRR algorithm.

[1] $|FM_{wc}(t1, t2)|$ denotes the worst-case value of $FM(t1, t2)$

IV. BANDWIDTH ASSIGNMENT USING OPPORTUNISTIC DRR (O-DRR)

To allocate bandwidth to the contending uplink flows, we devise a deficit round robin (DRR) based scheduling scheme that runs at the BS. Our scheme assumes that: (i) The channel between the SS and the BS is a Rayleigh fading channel, (ii) the coherence time of the channel is greater than the frame length (the IEEE 802.16 standard for point-to-multipoint network supports frame lengths of is 0.5 msec, 1 msec, and 2 msec), i.e., the channel does not change during a frame duration and (iii) that the SINR of each channel is known to the BS (which, as pointed out earlier, is obtainable from measurements at the physical layer).

We utilize DRR's idea of maintaining a quantum size Q_i and a deficit counter for each SS_i, which we term the lead/lag counter L_i. The BS also maintains an indicator variable $Flag_i$ for each SS. $Flag_i$ is 1, if SS_i is assigned bandwidth during a frame, and 0 otherwise. If, at a polling interval n during a scheduling epoch, $SINR_i$ is less than $SINR_{th}$, SS_i is not scheduled, and its quantum Q_i is distributed among the remaining SSs in proportion to their weights W_i (that we calculate shortly), while SS_i's lead/lag counter is *incremented* by Q_i, the amount of service it missed. Likewise, the lead/lag counter of an SS_j that received more than its minimum share Q_j of the uplink slots is decremented by the amount of slots that SS_j received over and above its quantum Q_j. The idea being to enforce fairness between different SS's in the long term. The weights W_i of the SSs are calculated based on the value of their deficit counters and their delay requirements. An active SS with a fast approaching delay bound is scheduled with a larger weight than an active SS with a relatively slowly approaching delay bound, independently of the class of traffic. Thus, in some cases, SSs with nrtPS traffic may have more weight than SSs with rtPS traffic.

We define a delay counter d_i for SS_i as follows:

$$d_i = T_{d(i)}(j) - nT_f, \qquad (7)$$

where $T_{d(i)}(j)$ is the T_d of an SS_i that belongs to the jth class of traffic (and is 50 msec for rtPS and 200 msec for nrtPS traffic) and n is the number of frames elapsed since SS_i was last scheduled. If nT_f exceeds $T_{d(i)}(j)$, then the delay constraint of SS_i is violated. Since we are using real-time (video) traffic in our simulations (for both rtPS and nrtPS traffic), we then drop the delayed packets/data and reset the delay counter value to the maximum permissible delay of SS_i, i.e., $T_{d(i)}(j)$.

We denote by l_i the length of the scaled deficit counter of SS_i, where l_i is obtained by adding the magnitude of the minimum deficit counter value among all SS's to the deficit counter of SS_i. (Note that this has the effect of scaling the deficit (or lag/lead) counter of each node to a non-negative value.) If for SS_i we denote by β_i, the reciprocal of the node's delay counter, then the weights for scheduling are defined as follows:

$$W_i = \frac{l_i \beta_i}{\sum_i l_i \beta_i}, \forall i \in active \ set. \qquad (8)$$

Observe that the above operation essentially computes a weight W_i for an SS_i that is proportional to a normalized product of the deficit counter and the delay counter. This makes intuitive sense, since we would like to give greater bandwidth to a user that has a smaller delay counter, because this indicates that the data in the queue of this user is close to reaching its delay constraint, and must therefore be scheduled with higher priority.

Algorithm 1 :O-DRR Algorithm for Multiclass Uplink Scheduling (at BS)

1: Set initial $k = k_{initial}$, the polling interval,
2: Set the *polling timer* $= kT_f$
3: **if** *polling timer* has not expired **then**
4:    BS polls and updates the $SINR$, Queue state for each SS
5:    BS updates the active list (L_{active}) of SS. ($i \in L_{active}$, if $(I(SINR_i > SINR_{th_i})) \wedge (Queue \ state_i ! = 0))$
6:    **for** $\forall i \in L_{active}$ of BS, check $SINR_i$ **do**
7:       **if** $SINR_i \leq SINR_{th_i}$ **then**
8:          Withdraw the BW assigned to SS_i and mark SS_i as "lagging" other SSs as "leading"
9:          Re-assign the withdrawn BW to "leading" SSs proportionate to their weights W_i.
10:      **end if**
11:      Update the delay counter d_i as per Eq. 7.
12:      Update the weights W_i of SS_i based on the lead/lag counter and delay counter as per Eq. 8.
13:   **end for**
14: **else**
15:    Update k (either with off-line values of k or by using the Eq. 6)
16: **end if**
17: Continue with step 2

V. SIMULATION MODEL AND EXPERIMENT

For our simulations, we assume an IEEE 802.16-based environment with a single BS and different sets of SS's for both single and multiclass traffic. We model only the time-dependent variations in the channel between a SS and the BS. We consider a population of $N = 100$ users (SSs) all of which either belong to a single-class (for the one class case), or are divided evenly into two classes of users (for the multiclass case), with a delay requirements of $T_{d(1)} = 200$ms and $T_{d(2)} = 500$ms, respectively. There is a single queue at each SS, which is assumed to be infinite.

The frame duration T_f is set equal to 1 ms, with $T_{ul} = 100$ slots per frame. Each simulation was purposely run for a heavy network load to tax the performance of our O-DRR schedule and ran for a period of 2500 frames (250,000 slots). The value of each parameter observed was averaged over 100 independent simulation runs, with the "warm up" frames (approximately 500 frames) being discarded in each run, to ensure that the values observed were steady-state values.

Using the optimization-based framework, described in Section III, we found a range of values of k (for the single-class case) and the worst-case (minimum) k for the two class case, which we fixed at $k = 100$ and $k = 75$ respectively.

To assess the efficacy of our O-DRR algorithm, we obtained the bandwidth allocated to each user for both the single-class and the multiclass case. We observe from Figs. 2, 3 that in both cases the users bandwidth allocations are within a small bound of one other. In fact, for $k = 75$, the average bandwidth allocated in the single-class case is 2000 slot equivalents and in the multiclass case is 1998 slot equivalents for class 1 and 2002 slot equivalents for class 2 which is very close to the average bandwidth of 2000 slots (200000 slots/100 users) that we would expect from a fair scheme. The maximum difference in allocated bandwidth is under 10 % of the average bandwidth for both. Fig. 4 shows the distribution of allocated bandwidth to users of both the classes for $k = 75$. We see that the bandwidth allocated is quite uniform as would be expected from a fair scheme.

An important performance benchmark of our scheme also is the extent to which it meets the delay guarantees of different classes of traffic. We measured this for the multiclass case by the percentage of traffic dropped from the queues at the SSs, which is shown in Fig. 5. We observe that the percentage of traffic dropped is less than 8.5 percent for both classes of traffic, even under the relatively heavy network load we considered. Since data is only dropped due to violations of its delay bound, this implies that with our scheme 91.5 percent of the incoming data meets its delay requirements.

Fig. 6 shows that Jain's Fairness Index [9], remains above 90% for a fairly large range of k, suggesting that it is possible for the provider to trade off fairness for delay by choosing an appropriate value of k at which the fairness and bandwidth requirements of different users are satisfied.

VI. CONCLUDING REMARKS AND FUTURE WORK

The results presented in Section V demonstrate that the O-DRR scheduler combined with our optimization-based polling scheme performs very well in terms of meeting our objective of providing fairness in bandwidth allocation while meeting the different delay requirements of diverse users in an IEEE 802.16-based network. Our scheme provides closed-form expressions for the polling interval, as well as a low-complexity scheduling algorithm for obtaining very good fairness-delay performance with multiclass traffic.

There are several directions of further work possible from here. One extension would be to look at adaptive modulation and coding schemes, where the link between an SS and BS may not only be in a binary state, but rather in one of a finite set of states with varying transmission rates, depending on the channel quality. Another would be to study the effect of location-dependent channel variations on the performance
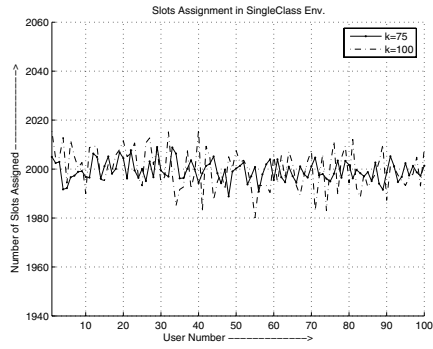
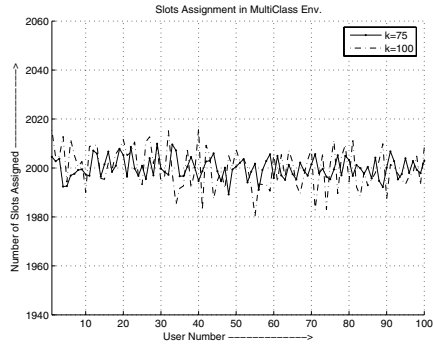Fig. 2.   Slots Assigned with a Single-class of Traffic

Fig. 3.   Slots Assigned with Multiclass of Traffic

of the proposed scheme. Some of these are under current investigation.

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[3] LAN/MAN Standards Committee, *IEEE Standards for Local and Metropolitan Area Network: Part 16: Air Interface for Fixed and Mobile Br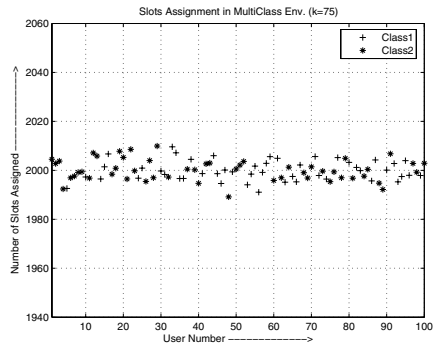oadband Wireless Access Systems (Amendments for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands)*. IEEE Computer Society and IEEE Microwave Theory and Techniques Society, September 2004.

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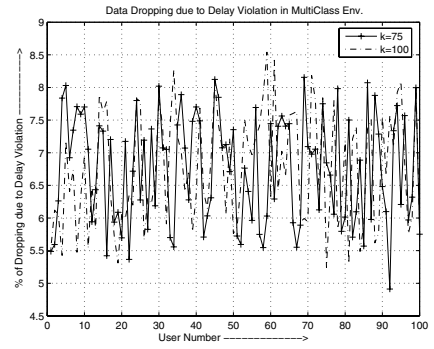
Fig. 5.   Data Dropped due to Delay Violation in Multiclass Env.
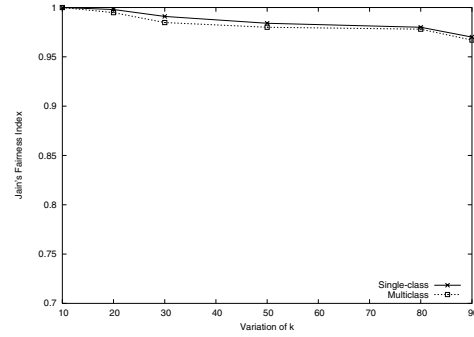
Fig. 6.   Fairness using Jain's Fairness Index for Single and Multiclass Env.

Fig. 4.   Slots Assigned with Multiclass of Traffic for $k = 75$