Adaptive Scheduling of Prioritized Traffic in IEEE 802.16j Wireless Networks

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***Abstract*—In this paper we propose an adaptive scheduling algorithm for IEEE 802.16j based wireless broadband networks. Computation of an optimal schedule for prioritized traffic in OFDMA based IEEE 802.16 wireless network is an NP-Hard problem. Hence, we propose a scheduling heuristic for an OFDMA based WiMAX relay network. The ORS (OFDMA Relay Scheduler) heuristic computes the zone boundaries (relay and access) in an uplink scheduling frame based on the number of RSs and MSs, the bandwidth demands and the link conditions. The ORS heuristic determines a schedule which assigns subchannels-timeslot to prioritized traffic based on the demand for various nodes while implementing frequency selectivity. The ORS adapts zone boundaries and the schedule to link and demand conditions at every scheduling period. We perform extensive simulations to demonstrate the effectiveness of adaptive zone scheduling and changes in rate conditions for various topologies.**

***Index Terms*—OFDMA, Scheduling, MMR WiMAX, Resource Allocation.**

I. Introduction

WiMAX technology, based on IEEE 802.16 standard is fast gaining momentum as the enabling technology for last mile wireless broadband access. In regions where wired infrastructure cannot be used due to prohibitive cost, geography limitations or hostile environment, WiMAX can provide connectivity in a cost effective and deployment-friendly manner.

There have been various amendments to the original IEEE 802.16 standard. We focus on the IEEE 802.16j standard that enables mobile multi-hop relay(MMR) based WiMAX. A MMR WiMAX network can increase coverage at a significantly lower CAPEX (capital expenditure) and OPEX (operating expenditure). This lower cost results from the deployment of relatively cheaper relay stations compared to the more expensive base stations. Relay based networks can increase throughput by using higher data rates. These data rates are achieved by using efficient modulation schemes that can be enabled at smaller hop distances. A MMR WiMAX network consists of a Base Station (MR-BS) and several Relay stations (RSs) and Mobile Stations (MSs) connected to the MR-BS through single or multiple hops. Unlike a multi-hop mesh network, a WiMAX relay network architecture is typically a tree, is compatible with the PMP mode and allows mobile broadband access.

In this paper we focus on adaptive scheduling in an IEEE 802.16j based network using OFDMA technology for prioritized traffic. The IEEE 802.16j standard specifies a frame structure that is divided into access and relay zones. The details of the frame structure are discussed in Section III. The zone boundaries may be adaptive, hence zone division would also be part of a scheduling algorithm for MMR WiMAX networks. In addition, depending on the type of relay stations used, scheduling could be centralized or distributed. Ideally, a scheduling scheme should be generic to both. IEEE 802.16j uses OFDMA technology that reduces multi-path fading and enables multi-user functionality with better spectrum utilisation. OFDMA technology divides the frame into a two-dimensional structure of timeslot-subcarrier slots. Slots could belong to different burst profiles, where a burst profile has a specific modulation and coding rate. A scheduling scheme for an OFDMA based MMR WiMAX network has to determine the slot assignment to applications in a prioritized manner such that their bandwidth demands are met.

The standard does not specify any particular scheduling scheme. To the best of our knowledge this is the first attempt to define an adaptive scheduling algorithm for prioritized traffic in IEEE 802.16j networks that also includes frame and zone division. A scheduler that optimises bandwidth utilisation for such a network has NP-Hard complexity [1]. Therefore, we propose a heuristic with an adaptive scheduling policy. The key features of the proposed ORS heuristic are:

1) Computation of zone boundaries adaptive to bandwidth demand and number of relay and mobile stations.
2) Schedule determination, that is, assignment of subcarrier-timeslot slots to prioritized traffic based on demand.
3) Frequency selectivity within a zone.
4) An adaptive scheduling policy that includes responsiveness to rate changes and link conditions and demands.

The rest of the paper is organized as follows. In Section II we discuss related work. We provide an overview of the IEEE 802.16j standard in section III. Section IV describes the ORS algorithm. We present our simulation results in Section VI. Section VII concludes the paper.

II. Related Work

Some of the scheduling schemes for wireless multihop networks schedule only one link at a time and hence they do not effectively utilize the capacity of the network [2], [3]. The objective of [4] is to formulate a scheduling problem which maximizes the system throughput under the defined fairness model. Jin et al. [5] address the problem of routing and packet scheduling for throughput maximization in IEEE 802.16 mesh networks. Tang, Xue and Zhang [6] studied bandwidth allocation in multi-channel multihop wireless mesh networks. They try to maximize network throughput while enhancing fairness. Scheduling and resource allocation for an OFDMA-based wireless network is addressed in [7]. A centralized scheduling scheme using multiple channels and single transceivers in a WiMAX Mesh Network is discussed in [8]. The authors in [9] propose a packet scheduling scheme in WiMAX Mesh Networks using bidirectional concurrent transmissions. Ryoulhee Kwak and J.M. Cioffi [10] focus on the subchannel allocation problem with power constraints for maximizing the sum-rate in downlink multi-hop OFDMA relay networks. Guoqing Li and Hui Liu [11] model the optimal source/relay/subcarrier assignment problem that maximizes the sum rate from all sources to the destination, with fairness constraint for OFDMA relay based networks. A generalized even-odd framework for link activation is proposed in [12] where the authors present techniques for constructing interference-free routes within the scheduling framework. The authors in [13] use the even-odd framework to guarantee the latency constraints and use dynamic programming to determine admitted flows. A heuristic based admission control and scheduling scheme based on the even odd framework is presented in [1].

III. IEEE 802.16j: An Overview

An IEEE 802.16j network consists of a Base Station (MR-BS), multiple Relay Stations (RSs) and Mobile Stations (MSs)([14]). Relay Stations can be of two types. Transparent relays serve MSs that are in range of the MR-BS and that receives control information from the MR-BS. The MS can receive signals from both the MR-BS and the relay and hence can achieve higher throughput. Non-transparent relays increase coverage area by serving MSs that cannot decode control information from the MR-BS. These relays must transmit control information at the beginning of the frame and act as the base station for the MS. IEEE 802.16j focuses on the OFDMA PHY mode of IEEE 802.16e-2005. There are five different service classes of traffic defined in the standard are shown in Table I.

TABLE I
Service Classes in WiMAX

Class	Application	QoS parameters
Unsolicited Grant Service (UGS)	VoIP,E1; fixed-size packets on periodic basis	max rate, latency and jitter
Real-Time Polling Service (rtPS)	Streaming audio/video	minrate, maxrate and latency
Enhanced Real-Time Polling Service (ertPS)	VoIP with activity detection	minrate,maxrate, latency and jitter
Non Real-Time Polling Service (nrtPS)	FTP	minrate and maxrate
Best Effort (BE)	Data transfer, Web	maxrate

A WiMAX network can have different modulation and code rates depending on Carrier to Interference-plus-Noise Ratio and Received Signal Strength Indication (RSSI) values at various links. Each modulation and code rate supports a different data rate. An IEEE 802.16j frame consists of a downlink subframe followed by an uplink subframe. We consider only uplink traffic in this article and hence discuss only the uplink subframe. In [15], the authors mention that the IEEE 802.16j working committee has proposed a scheduling framework in the IEEE 802.16j draft in which only one node is allowed to transmit at any given time instant during the downlink subframe. This would be a significantly simpler problem and we could easily limit the described uplink model to accomodate it.

1) Transparent relays :The uplink subframe is divided into access zone and relay zone. Access zone is used by MSs to transmit on access links to the MR-BS and RSs. The relay zone is used by relay stations to transmit to their superordinate RSs or MR-BS. All transparent relays must operate in centralized scheduling mode, relying on the MR-BS to allocate its resources.
2) Nontransparent relays: The uplink subframe is divided into access zone and relay zone. This presents some challenges in a multihop scenario. For example, in Figure 1 when there are two relays (NT-RS1 and NT-RS2) between MR-BS and MS2. In this case, in the relay zone NT-RS2 transmits to NT-RS1 and NT-RS1 transmits to MR-BS. Thus NT-RS1 has to transmit and receive at the same time. There are two ways of solving this problem. One is to include multiple relay zones in a frame and relays can alternately transmit and receive in the different zones. The other approach is to group frames together into a multi-frame and coordinate a repeating pattern in which relays are receiving or transmitting in each relay zone. We adopt the first approach of multiple relay zones in a frame. We divide the relay zone into an even relay and an odd relay zone (Figure 2). We label each relay alternately as even or odd. MR-BS is labeled even and the children of MR-BS are labeled odd and so on. Even relays transmit in even relay zone and odd relays transmit in odd relay zone. Non-transparent relays may operate in both centralized and distributed scheduling mode.

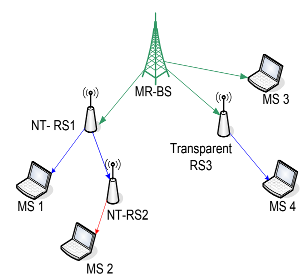

Fig. 1. IEEE 802.16j Network

IV. The OFDMA Relay Scheduler Algorithm

We try to address three different problems in this paper.

- Division of an IEEE 802.16j frame into different zones based on bandwidth demands, the number of MSs and RSs and the conditions at different subchannels of a link.
- Class differentiated schedule determination at different nodes based on subchannel conditions and bandwidth demands.
- Rescheduling policies if the rates increase or decrease for some slots.

We propose a heuristic algorithm, OFDMA Relay Scheduler (ORS) algorithm, for IEEE 802.16j network. The ORS algorithm is used to schedule traffic for every MS/RS in each scheduling period. A scheduling period consists of an integral

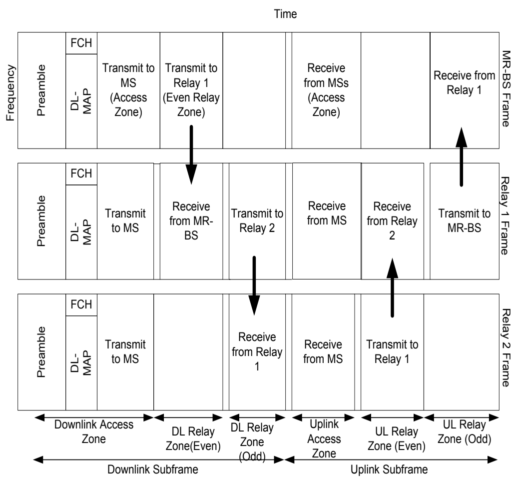

Fig. 2. IEEE 802.16j Frame Structure

number of frames. The same schedule is followed in all the frames of a scheduling period unless there is change in rate of any slot that may require rescheduling as described later in the section. Note that a slot is identified by a timeslot-subchannel combination in an OFDMA frame. We divide the scheduling problem into two parts.

1) Frame division and Bandwidth Estimation
2) Slot Scheduling

There are three scenarios in an IEEE 802.16j based relay network:

1) The MS is connected to the BS.
2) The MS is connected to the BS using a transparent relay.
3) The MS is connected to the BS using one or more non-transparent relays.

The ORS scheduler works for all three scenarios. We focus on the centralized model. In the centralized model the BS allocates slots for all nodes (MS and RS) in the network. At present we assume that the nodes are synchronized and the impact of clock skew will be studiied in future work. We use the Traffic Admittance (TA) metric for evaluating the ORS scheduler.

A. *Traffic Admittance*

Traffic Admittance (TA) is the weighted proportion of admitted to the demanded traffic over all the nodes. Traffic is said to be admitted if it has been allocated required slots from the source to the destination, the MR-BS in this case. Hence TA can be defined as:

$$TA = \frac{\sum_i w_i A_i}{\sum_i w_i T_i} \tag{1}$$

where w_i is the weight associated with a particular service class, A_i is the admitted traffic of that class and T_i is the total traffic demand for that class.

B. *Frame division and Bandwidth Estimation*

An IEEE 802.16j frame is divided into access and relay zones. The access zone is used by MSs to transmit to their parent and the relay zone is used by RSs to transmit to their superordinate RS. We divide the relay zone into even and odd relay zones to maintain the half-duplex nature of the nodes. Nodes at alternate levels are labeled even or odd alternately. Even nodes transmit in even relay zone and odd nodes transmit in odd relay zone. The MR-BS is assigned an even label. Thus the children of MR-BS are labeled odd. The same frame boundary (division into access, even and odd relay zones) is used throughout the network as the half-duplex constraints may be violated if different boundaries are used. However the frame division may change at every scheduling period depending on the bandwidth requirements of different nodes and the rates of various slots for the different links.

In an OFDMA network; capacity estimation is a complex problem. This is because each time-frequency slot could be modulated to a different rate depending on the RSSI and CINR values for the subchannel on the link to which the slot is assigned. However slots are assigned based on criteria like aggregate demand, proportional fairness, priority etc. each of which involves an estimate of individual slot capacity or network capacity. We compute the lower bound of the network capacity by assuming all the slots available for data transmission are modulated at the most robust and least rate. When the MR-BS does not know the CINR, RSSI values of the subchannels at various links it assumes that the subchannels have the the minimum, most robust rate. When the MR-BS obtains information about the CINR and RSSI values at various links, it can determine the data rate used by the subchannel. The MR-BS uses the estimated rate information for each link and subchannel to compute slot requirements for each node. If the RSSI/CINR values for a particular subchannel for a link causes the link to be unable to support even the lowest rate, it is marked unusable. The subchannel for the link is marked unusable until the CINR/RSSI value of that (subchannel, link) is able to support a higher rate. Our algorithm assumes that the MR-BS, RSs and MSs exchange REP-REG and REP-RSP messages regularly. So the channel condition is updated at regular intervals. Hence the rate supported by a particular (subchannel, link) is known before every scheduling period.

The bandwidth demand of a particular link i is denoted by bw_i and the link's rates for the various subchannels are denoted by $r_1, ..., r_k$. Let r_{avg} be the mean rate of all these rates. We use a mean rate instead of the minimum rate since a single poorly performing subchannel could skew the scheduling process. The number of slots required by link i is bw_i/r_{avg} rounded to the nearest high integer value subject to the condition that the total number of slots are not higher than the frame size. The algorithm computes the number of slots required by every link in this way and divides the frame into different zones as described below.

We use M to denote MSs connected directly to the MR-BS, MT to represent MSs connected to a transparent relay, MR to denote MSs connected to non-transparent relays and NR to denote the non-transparent relays and TR for transparent relays. All the nodes send their aggregate bandwidth demand for a particular service class to the MR-BS. In our proposed scheme the MR-BS computes the aggregate demand of each node based on the bandwidth requests and calculates the slot requirements based on the aggregate demand and the link rates. Let these be represented as

$Ma_1, Ma_2, NRa_1, NRa_2, NRa_3, TRa_1, TRa_2, MTa_1, MRa_2$ and so on where a represents the aggregate slot demands. The MR-BS then computes the sum of the aggregate demands of all the MS's connected to it directly and of all the MS's connected to it using transparent relays. $SumAccess = Ma_1 + Ma_2 + MTa_6 + ...$ It then obtains the Access Zone Proportion as follows.

$$AccessZoneProportion = \max(SumAccess, childMS(NRa_1), childMS(NRa_2)....childMS(NRa_n))$$

where $childMSN(Ra_i)$ represents the sum of the slots of the MSs under non-transparent RS i. The above expression tells that the maximum number of slots required by an access zone will be the maximum slot demand of the MSs at any level under MR-BS or a particular RS.

The MR-BS also computes the sum of aggregate slot requirements for the even relays and the same for the odd relays. These can be represented as

$$ORZoneProportion = NRa_1 + NRa_3 + NRa_5 + ... + TRa_1 + TRa_2 + TRa_3 + ...$$

$$ERZoneProportion = NRa_2 + NRa_4 + ...$$

Note, that the relays are numbered odd and even alternatively based on their hopcount from the MR-BS. Hence, the proportions in which the frame will be approximately divided using the estimated slot requirements will be $AccessZoneProportion$, $ORZoneProportion$ and $ERZoneProportion$. We assume that transparent relays are only one hop from the MR-BS.

In a distributed model, the MR-BS does not have knowledge about the subtree under any of the non-transparent relays. For computing $AccessZoneProportion$ the MR-BS determines the maximum of the slot demand of all the MSs under it and all children RSs. For the $ORZoneProportion$, it will compute the sum of the aggregate slot demands of the relays that are one-hop child of the MR-BS. The $ERZoneProportion$ will be determined by the maximum of the aggregate slot demands of all the non-transparent odd relays. This is because for a specific non-transparent relay, the total demand of its child relay nodes will at most equal its own demand. Also we assume that child relay nodes or MSs belonging to two different relay parents will not interfere and hence can be scheduled at the same time. WiMAX is applicable to metropolitan area networks, so deployment would ensure that relay nodes are significantly apart.

C. Slot Scheduling

The ORS heuristic schedules slots for a particular service class to all the nodes in a zone before considering the next zone. Once the bandwidth requirements for a particular service class has been met in all zones, the next service class is considered. The proper zone where the slots for a particular node will be allocated is based on whether the child is a MS or RS and the label of an RS. The node is then allocated slots based on the best available subchannels for that link. An available subchannel is picked for scheduling a link based on its CINR, RSSI values so as to use the highest possible modulation rate. If the CINR and RSSI values of a subchannel for a link is not known, the MR-BS assumes that it is the lowest rate. The ORS heuristic attempts to allocate slots on the same or adjoining subchannels since these will provide similar performance and may also result in lower number of bursts. However minimizing the number of bursts is not a goal of this work. The algorithm computes $bandwidthreserve$ for each node which is determined by the proportion of slots to be allocated to the node for a specific service class based on the aggregate demand for the service class by the node and the total slots in that zone. ORS maintains a $bandwidthalloted$ counter that adds up the bandwidth used by each slot assigned. When this number reached the $bandwidthreserve$ for the node, the scheduler starts scheduling for the next node, in a round-robin manner. There may be surplus bandwidth left after completing one round since the slots would have different modulation rates and if the estimated bandwidth was lower than the available bandwidth. The remaining slots is distributed in the same proportion for the remaining demand. Nodes whose aggregate bandwidth demand has been satisfied for this class are excluded from the next round of allocation. Once the demand of all the nodes for this service class is satisfied, a new proportion is computed based on the aggregate demands of the next service class from the nodes. In centralized scheduling the MR-BS determines the bandwidth allocated to a MS or RS and the slot assignment. However the PDUs that are transmitted in a particular slot is determined by the MS/RS.

V. Adaptive Scheduling Period

A scheduling period is defined as an integral number of frames over which a schedule holds. Typically, a scheduling period is more than one frame since the cost of computing and disseminating a schedule at every frame is too high. However, a fixed scheduling period does not reflect the dynamic nature of wireless networks. Varying link conditions and client mobility are key characteristics of wireless networks. The ORS uses a policy of adaptive scheduling period. The scheduling period is varied based on the stability, rate increase/decrease and the change in demand in the network. It is bounded by SP_{max} and SP_{min}. SP_{max} is the maximum number of frames in any scheduling period. It should be such that the changes in the bandwidth demand are reflected in a schedule in a reasonable time as determined by experiments. The minimum scheduling period SP_{min} satisfies the condition

$$C + hd < SP_{min} . f \quad (2)$$

where C is the cost of computing a schedule, h is the number of hops in the network, d is the total delay at each hop, f is the frame size. SP_{min} is the least integer that satisfies the above condition.

During bootstrapping, the scheduling period is set to SP_{max}. Whenever there is a reschedule based on rate increase or decrease, the ORS determines the condition for evaluating the scheduling period. If the condition is met, the scheduling period is halved. This continues until the scheduling period becomes SP_{min}. The heuristic keeps a history of M frames where $M \geq SP$. If there is no potential reschedule within M

frames, we double SP. The doubling keep on happening till SP becomes SP_{max}.

A. Rate Increase

The ORS keeps track of the number of potential rate increases in a scheduling period. If the number of rate increases is greater than a specified $Threshold$ increase, the heuristic determines whether to reflect the rate increase. The $Threshold$ value is used to determine the stability of the link and reduce any ping-pong effects of consecutive rate increase and decrease. The heuristic determines whether the number of frames since the last scheduling period is greater than or equal to the SP_{min}. This is to ensure that the cost of recomputing and disseminating a new schedule is not a limiting factor. If this condition is met, then the heuristic evaluates the following condition

$$(\sum s_i(r_i^{new} - r_i^{old}) \geq p \sum s_i * r_i^{old}) \\ \cap (Bw - \sum s_i r_i^{old} > 0)$$

In the first half of this condition, s_i denotes a particular slot, i; r_i^{new} and r_i^{old} refers to the new and old rate of the slot respectively. If there is no rate change for this slot then new and old rates are equal. p denotes a percentage value that can be specified by the network administrator. This is primarily used to determine whether the gain in the throughput would justify the recheduling cost. We use throughput here instead of traffic admittance metric used for comparing our simulation results, since TA value cannot be obtained without recomputing the schedule. The second half of this condition quantifies whether there is any unsatisfied demand. If there is no unsatisfied demand, then the reschedule can be deferred since there is no gain in throughput to be obtained. Bw refers to the current bandwidth demand and $\sum s_i * r_i^{old}$ denotes the satisfied bandwidth demand If this condition evaluates to true, the heuristic initiates a reschedule and halves the scheduling period. The halving may continue till SP reaches SP_{min}.

B. Rate decrease

Rate decrease may be across multiple subchannels or affect multiple links. If there is a rate decrease, the total bandwidth allocated to a node decreases and the node may not be able to provide the minimum guaranteed rate to its flows. Hence the MR-BS (centralized scheduling) or parent of the node affected by the rate decrease (distributed scheduling) has to check if there are any free unused slots available and allocate the extra slots (based on the difference between the previous and current bandwidth) to the node. The MR-BS/parent checks if any BE flows can be terminated on that node or any other children. If the bandwidth demand of the real-time traffic is still not met but the link can still support the most robust rate, the heuristic initiates a reschedule. However, if the link is unable to sustain the minimum most robust rate on all the subchannels it is currently using then it implies the link may be failing. The heuristic, then initiates a re-route and reschedule process. The routing algorithm attempts to discover a more robust path. A 'more robust path' is defined as one, every link of which has a CINR/RSSI value better than required to sustain the most robust rate by a value of α. The value of α should deter ping-pong effects by reducing the effect of migrating to an equally poor or poorer path. If a more robust path is found the traffic on the failing link is re-routed to this path and a new schedule is computed, otherwise a new schedule is computed eliminating the traffic on the failing link. Whenever a new schedule is computed we decrease the scheduling period SP by half until a minimum value of SP_{min}.

If a previously unusable link is able to support the minimum most robust rate, and maintains/improves its quality for H frames, a rerouting algorithm determines whether any traffic can use that link. A rescheduling is then done.

VI. Simulation Results

A. Methodology

We perform our evaluations on a number of different IEEE 802.16j networks. Two representative topologies are illustrated in figures 3 and 4. Topology 1 has a higher number of hops and MSs connected to the MR-BS, while Topology 2 is more like a binary tree topology with a linear chain on the left hand side. The number of nodes in such networks is usually small because of the large range of the BS and RSs.

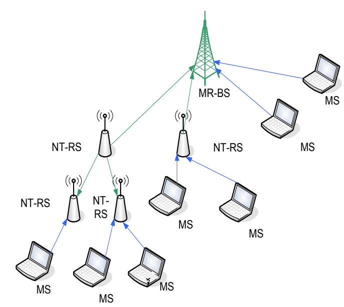

Fig. 3. Topology I

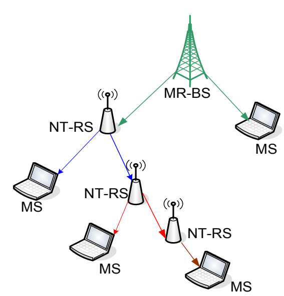

Fig. 4. Topology-II

We implement the heuristic algorithm using a custom simulator written in C. The simulator logically comprises of three parts; the flow generator, the scheduler and the adaptivity moderator. The user can input any tree topology. We used multiple such topologies for generating the results, for example, Figures 3 and 4. The flow generator generated flows according to Poisson arrival process. The lifetime of a flow is exponentially distributed and used to generate the departure time of the flows. The number of flows generated per set could be different each time because the type of flows are also generated randomly. Each type is associated with a different bandwidth range. We use a uniform random generator to generate the source of the flow. Each flow has an associated route that is computed from the source generated by the flow generator and the topology input by the user. In these simulation, we consider only uplink flows although our simulator can be easily extended to schedule for both uplink and downlink. Each flow has an associated route that is computed from the source and destination generated by the flow generator and the topology input by the user. The frame length and maximum number of subchannels are configurable.

Every node computes the aggregate bandwidth requirement per traffic class that it requires. This includes the demands of all its descendant nodes. The scheduler then computes a feasible schedule for the current frame in a class prioritized manner. This comprises of computing the zone boundaries as well as timeslot-subchannel allocation for traffic within each zone as described in section IV. Initial rates for subchannels per link are read from a file to enable the decision of which subchannel to choose at every link as well as to compute the number of slots required. For every hop for each service class the scheduler allocates bandwidth in a round-robin manner in proportion of the traffic requirement of the nodes for that service class at that hop. The schedule for each link computed by the scheduler is stored as a two dimensional structure of subchannels indexed by timeslots. The goal is to allocate only for the minimum bandwidth requirement for the traffic belonging to each service class.

The adaptivity moderator keeps track of the threshold values. It changes the rates of randomly chosen subchannels for arbitrary chosen links at every frame. It also arbitrarily changes the demand, that is, the bandwidth requirements at randomly chosen nodes at every frame. Based on these changes and the threshold values, it evaluates the conditions for effecting a re-schedule before the completion of the current scheduling period. If the scheduler is executed before the end of the current scheduling period then the adaptive moderator also changes the scheduling period as per the heuristic algorithm to reflect the same.

Results are compared based on the *traffic admittance* (TA) values. We assume that the weights for the traffic classes are in linear proportion based on the price comparison figures for different plans by various network providers [16], [17]. We obtained results for the following:

1) Adaptive zone allocation vs fixed zone allocation
2) Effective rate change and its comparison with the minimum and maximum bounds
3) Rate Increase
4) Rate Decrease

B. Adaptive zone allocation vs fixed zone allocation

In this section we evaluate the efficiency of adaptive zone allocation as compared to fixed zone allocation in terms of TA values obtained for different flow sets. The input flow sets used were the same for both. In case of adaptive zone allocation the access zone and odd and even relay zones are computed based on the proportion of traffic demands as explained in section IV. For fixed zone allocation we divided the uplink subframe into three equal parts, one each for access zone and odd and even relay zones. The results are depicted in Figure 5. Clearly, adaptive zone allocation yields better TA values than the fixed zone allocation. This is because the adaptive zone allocation accounts for both topology as well as link demands, while the fixed allocation uses neither. The computation times of both the algorithms were comparable and have not been shown because of space constraints. Hence, adaptive zone allocation is more efficient than fixed zone allocation. It may be argued that different proportion of fixed allocation may provide a better result. This may be true for some specific traffic scenarios but not all. Note that in the simulations, we aggregated the results obtained for each set of input over a number of topologies.

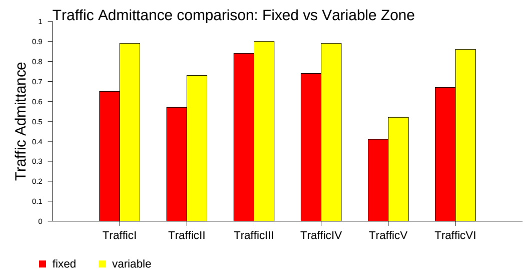

Fig. 5. Adaptive Zone vs Fixed Zone Allocation

C. Effective rate change compared with Min and Max bounds

We obtain the TA values for a number of traffic sets assuming all the subchannels at all the links set to the minimum possible rate. This defines the minimum bound. We also obtain the TA values for the same flow set assuming all the subchannels at all the links working at the maximim possible rate. This sets the maximum bound. Assuming all subchannels functioning at the minimum rate we double the rates of all the subchannels at all the links and obtain the TA value. We double the rates again. The results for topology 1 are presented in figure 6.

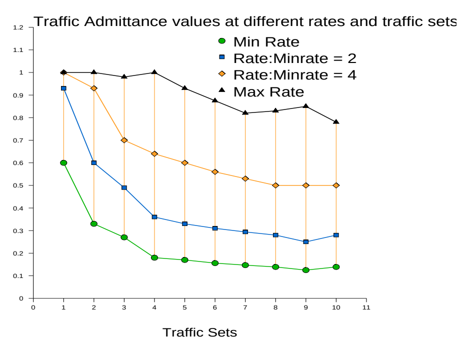

Fig. 6. Topology 1: Effective Rate Change compared to Min and Max bounds

The figure indicates that for multiple traffic sets, the algorithm responds very well to the rate increases and shows a proportional increase in the TA values. We obtained similar results for other topologies including topology 2 that are not shown here because of space constraints.

D. Rate Increase

Figure 7 depicts the increasing trend of the TA values with contiguous rate increases in two different topologies for the same traffic set. Note that the rate increase is not uniform over all the subchannels and links as was in the previous result.

Subchannels and links have been randomly chosen for the rate increase. The increase in the TA value depends on the chosen links and the traffic demands on those links or child links. For instance, if any of the bottleneck links are chosen, the increase in the TA value is higher than if a link to a leaf node is chosen. Hence, while a specific pattern cannot be discerned because of the randomness in choosing the links and subchannels however, a definite increase in the TA value is seen. This is because the links chosen had unsatisfied demand. This depicts the responsiveness of the adaptive algorithm to the rate increase.

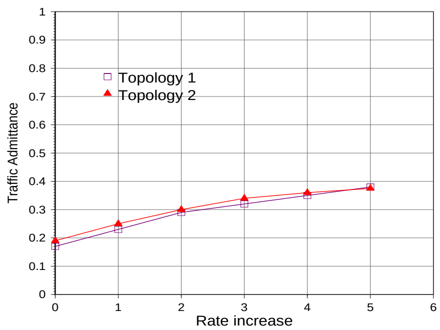

Fig. 7. Adaptivity to contiguous rate increase

E. Rate Decrease

Figure 8 depicts the decreasing trend of the TA values with rate decreases in the two topologies for the same traffic set. The rate decrease is not uniform over all the subchannels and links. Subchannels and links have been randomly chosen for the rate decrease. While initially the decrease in rate does not cause much difference in the TA values, gradual rate deterioration result in the decreased TA values in both the topologies. The initial stability is because the scheduling algorithm re-computes the zone partitioning to compensate for the decreased rate. Topology 1 performs better than Topology 2 as a result of frequency selectivity. This is because Topology 1 has 2 MSs connected directly to it whereas Topology 2 has only 1 MS. Hence, when the rate of a subchannel associated with an access link for Topology 1 was decreased, the scheduler used that subchannel for the other MS for whom the rate was unchanged. Hence the overall TA value did not deteriorate.

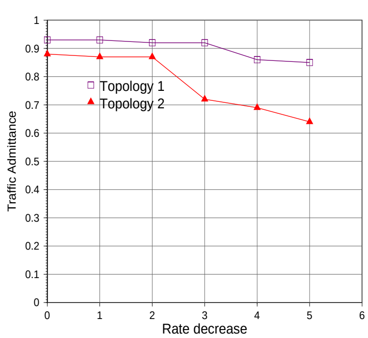

Fig. 8. Adaptivity to contiguous rate decrease

VII. Conclusion

In this paper we addressed the problem of an adaptive scheduling algorithm for IEEE 802.16j based wireless broadband networks. We presented a heuristic algorithm, the OFDMA Relay Scheduler (ORS). The ORS

1) Adaptively computes access and realy zone boundaries based on current traffic demand and subchannel rates.
2) Determines a demand proportional schedule for prioritized traffic using some frequency selectivity within a zone.
3) Adapts to link conditions: rate increase and/or decrease.
4) Implements an adaptive scheduling period based on traffic demand and link conditions.

To the best of our knowledge, this is the first such algorithm that comprehensively addresses adaptive zone boundary computation, determination of schedule for prioritized traffic based on traffic demand while incorporating frequency selectivity within a zone and adapting to changing link conditions in IEEE 802.16j networks.

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