Adaptive Bandwidth Provisioning in IEEE 802.16 Broadband Wireless Networks

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Abstract—**Congestion based pricing algorithms are considered efficient approaches to control congestion and to distinguish services provided for users in computer networks. Game theory lends itself as a prevailing tool to design such algorithms. In this work, we propose a game theoretic congestion based bandwidth provisioning algorithm to address the scarcity for bandwidth provisioning scheme in IEEE 802.16 standard. To the best of our knowledge, the proposed algorithm is the first one to simultaneously control congestion and fairness while providing differentiated QoS guarantees. Simulation results reveal that the proposed scheme realizes our objective of controlling congestion, and provides differentiated QoS guarantees and proportional fairness among the different network classes.**

I. INTRODUCTION

The explosive growth of the Internet over the last decade has lead to an increasing demand for high-speed, ubiquitous Internet access. IEEE 802.16/WiMax is today's most promising new technology for broadband wireless access to IP services. WiMax can serve a wide range of applications including data, voice, gaming, and multimedia. However, WiMax is challenged by meeting diverse QoS requirements of these applications over a finite radio spectrum. This implies more complex network planning and resource management and requires sound new approaches to ensuring QoS. To address some of these issues the IEEE 802.16 standard [1] defines a service flow framework that supports multiple service flow classes; Unsolicited Grant Service (*UGS*), real time Polling Service (*rtPS*), non-real-time Polling Service (*nrtPS*), Best Effort (*BE*) and Extended real time Polling Service (*ErtPS*). The IEEE 802.16 standard framework maps each traffic connection into one service flow class, once a Subscriber Station (SS) joined a network and a connection bandwidth request is accepted. Bandwidth requests by the SSs are always on per connection basis, while bandwidth grants by the base station (BS) can be either using grant per connection (GPC) or grant per subscriber station (GPSS).

IEEE 802.16 standard did not define a packet scheduler. However, numerous schedulers have been proposed recently to cater for the scarcity of a scheduling mechanism in the standard. The current work in this field can be categorized into two categories; proposals that utilize well-known schedulers such a Weighted Fair Queuing (WFQ) as an uplink and/or downlink WiMAX schedulers [4], [5], [6], [7], [8], [9] and opportunistic schedulers based on cross layer optimization [10], [11], [12], [13], [14]. The study in [15] shows that the current proposals for WiMAX scheduling cannot provide proportional fairness among classes while meeting the diverse QoS requirements of applications supported by service flow model of WiMAX. The later work in addition to the fact that there is not any algorithm that address the issue of controlling congestion in WiMAX network based on congestion based pricing motivated the work in this paper. In this paper, we propose a bandwidth provisioning algorithm with two objectives; controlling congestion in the WiMAX network through introducing a pricing parameter in a market based scheme. The Base Station (BS) station varies the pricing factor based on the traffic load in the network. The other objective is to provide logarithmic proportional fairness among the different classes of the network. We note here that our algorithm is a general algorithm and can be implemented in any wireless network; i.e. WiFi, HSDPA, WiMAX,..etc. However, we implemented it over a WiMAX network with four classes to evaluate the proposed algorithm performance.

Different parameters can be considered in designing a good bandwidth provisioning algorithm. The ones which can be considered as best characteristics of a good provisioning algorithm are the followings:

1) enforce the various classes QoS requirements,
2) capture and make use of the technology physical and functional specifications,
3) efficiently provide for wide range of QoS requirements
4) gratify for fairness among classes and
5) adapt to network status, specifically network congestion

Game theory lends itself as a useful and powerful tool for designing an efficient resource management schemes with the above characteristics and under congested network environments. The basic idea of game theory is how strategic interactions between rational players (sometimes called agents) generate outcomes according to the players' conflicting preferences [2], [3]. Thus, Game theory can establish a suitable framework to capture more insight into the interactions of self-interested players with potentially conflicting interests.

In this paper, we adopt a non-cooperative congestion based price game at the BS to calculate the time slots of a given time frame to the different class services in a WiMAX based networks. We define four players correspond to four service flow classes of the IEEE 802.16 standard: ErtPS, rtPS, nrtPS, and BE. Each player is associated with a utility function which is a weighted sum of logarithms of a ratio of the

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class proportions of time slots of WiMAX time frame to the summation of other classes' time slots. The utility function is defined as such to address fairness among the different service classes. A pricing factor is introduced to penalize any greedy service classes and control network congestion.

We proceed by formulating the problem in Section II, discuss the performance evaluation and results in Section III, and conclude the paper in Section IV.

II. BANDWIDTH PROVISIONING APPROACH

We propose an algorithm to be implemented at the Base Station (BS) in a single cell consists of one BS with several Subscriber Stations (SS) in a PMP mode or in a IEEE 802.16j multihop relay network at the network gateway in a tree based infrastructure.

It is assumed that the BS has complete channel state information of all connections through a robust feedback channel. A subscriber station (SS) conveys its received signal to noise power ratio (SNR) from itself to the BS. Therefore, this information is not changing over one time frame, since the wireless channel between each SS and BS is assumed to undergo a flat fading that is fixed over one frame period. The adaptive modulation coding (AMC) module described in IEEE 802.16 standard [1] divides the range of the received Signal to Noise Ratio (SNR) into seven non-overlapping regions. According to the received SNR at a specific SS, the BS decides the suitable transmission mode and consequently the data rate for each SS.

A. Mathematical formulation

The proposed bandwidth provisioning algorithm is designed to calculate number of time slots per each class. Allocating time slots within one class is out of the scope of this paper. However, any appropriate WiMAX schedular can be realized to allocate time-slots among the class active connections.

The proposed algorithm isolates the service classes by allocating K_i time-slots for each class i out of K total time-slots in a given time frame.

In IEEE 802.16, time frames are divided into constant number of time slots with same time-slot duration, however, the slot duration in bits may change on frame bases depending on the AMC mode as a result of the channel condition. The total K time-slots are completely partitioned among the classes such that the difference between a utility function and a pricing function is maximized. The utility function role is to allocate the frame time-slots to the different service classes optimally to guarantee proportional fairness among the different service classes. While the pricing function is introduced to prevent greedy demand of time slots and control congestion.

$$\begin{aligned} \text{P1:} \quad & \max_{K_i \in \mathcal{K}_i} \left\{ L(K_i, \mathbf{K}^{-i}) = U_i \log\left(1 + \frac{K_i}{\Upsilon_i}\right) \right. && (1) \\ + \quad & \psi_i \log(K_i - \rho_i K_{i,min}) && (2) \\ - \quad & \left. \lambda K_i \right\}, && (3) \end{aligned}$$

where $\Upsilon_i \triangleq v_i + \sum_{m \neq i}^{4} K_m$. The set of class i's time slots is denoted by $\mathcal{K}_i = [K_i^{min}, K_i^{max}]$. The utility function in (1) is to provide proportional fairness among the different service classes. The utility factor U_i is a measure of how much class service i is willing to pay. The barrier function in (2) is to guarantee that the new allocated time slots will be enough to support the payload of all active connections of class i, $U_i \gg \psi_i$. ρ_i is a tuning factor introduced to provide the service provider with the flexibility to decide how much resources he would like to allocate for classes above their minimum requested time-slots, $K_{i,min}$. The effect of ρ_i can be disabled, if required, by choosing $\rho_i = 1$. A linear pricing function in (3) with pricing factor λ is introduced to prevent the greedy use of network resources and control congestion.

To write problem P1 as a formal game theoretic problem, we define $x_i \triangleq \frac{K_i}{\Upsilon_i}$, $x_i \in \mathcal{X}_i$, with $\mathcal{X}_i = [x_i^{min}, x_i^{max}]$ being the action profile or the strategy space of the ith player (service class). Consequently, the objective function in problem P1 is modified as follows

$$\text{G1}(x_i, \mathbf{X}^{-i}, \lambda_i): \quad \max_{x_i \in \mathcal{X}_i} \left\{ L_i(x_i, \mathbf{X}^{-i}, \lambda_i) \right\}, \forall\, i \in \mathcal{I}, \quad (4)$$

with $L_i(x_i, \mathbf{X}^{-i}, \lambda_i)$ given by:

$$\begin{aligned} L_i(x_i, \mathbf{X}^{-i}, \lambda_i) &= U_i \log(1 + x_i) && (5) \\ &+ \psi_i \log(x_i - \rho_i\, x_i^{min}) - \lambda_i\, x_i && \end{aligned}$$

$\text{G1}(x_i, \mathbf{X}^{-i}, \lambda_i)$ is a non-cooperative game with pricing (NGP) in which the player i (QoS service class i) based on local information $(\mathbf{X}^{-i}, \lambda_i)$ decides its next decision x_i that maximizes its objective function $L_i(x_i, \mathbf{X}^{-i}, \lambda_i)$. The vector of players' actions (decisions) is denoted to by $\mathbf{X} = (x_1, x_2, x_3, x_4)$, while $\mathbf{X}^{-i}$ is the vector $\mathbf{X}$ without the ith element. The pricing factor, to prevent a greedy usage of the time slots resource, λ_i is equal to $\lambda\, \Upsilon_i$. Finally, $\mathcal{I} = \{1, 2, 3, 4\}$ is the indexing set of the players.

The limits of the action profile $\mathcal{X}_i$, namely x_i^{min} and x_i^{max} are set such that $\Upsilon_i\, x_i^{min} = K_i^{min}$ and $x_i^{max}\, \Upsilon_i = K_i^{max}$, respectively.

The optimal value x_i^* that maximizes $L_i(x_i, \mathbf{X}^{-i}, \lambda_i)$ (simply L_i) in (4) is the feasible solution of the following equation:

$$\frac{\partial L_i}{\partial x_i} = \frac{U_i}{1 + x_i} + \frac{\psi_i}{x_i - \rho_i\, x_i^{min}} - \lambda_i = 0, \forall\, i \in \mathcal{I} \quad (6)$$

or

$$x_i^2 - \Xi_i\, x_i + \phi_i = 0 \quad (7)$$

That is,

$$x_i^* = \frac{\Xi_i}{2}\left(1 + \sqrt{1 - \frac{4\,\phi_i}{\Xi_i^2}}\right), \forall\, i \in \mathcal{I} \quad (8)$$

where $\Xi_i \triangleq -1 + \rho_i\, x_i^{min} + \frac{U_i + \psi_i}{\lambda_i}$ and $\phi_i \triangleq -\rho_i\, x_i^{min} - \frac{\psi_i - U_i\, \rho_i\, x_i^{min}}{\lambda_i}$. Then the optimal number of time slots of the service class i, K_i^* can be expressed in terms of x_i^* as follows:

$$K_i^* = x_i^* \Upsilon_i, \forall i \in \mathcal{I} \quad (9)$$

In order to guarantee that $x_i^* > 0$, the utility factor U_i should be picked such that

$$U_i > \lambda_i\,(1 - \rho_i\, x_i^{min}) - \psi_i \quad (10)$$

B. Existence of Nash Equilibrium Operating Point

In this subsection we demonstrate the existence of Nash Equilibrium (NE) operating point in the game G1 using the classical results of game theory. The existence of a NE point is guaranteed if the objective function is quasiconcave and optimized on a convex strategy space [3]. We denote the NE operating point by $\mathbf{K}^*$ (allocated time-slots vector of the four different service classes) where $\mathbf{K}^* = (K_1^*, K_2^*, K_3^*, K_4^*)$, and at equilibrium K_i^* is given by

$$K_i^* = x_i^* \, \Upsilon_i^* = x_i^* \left(\sum_{m \neq i}^{4} K_m^* + v_i \right), \forall i \in \mathcal{I} \qquad (11)$$

To prove the existence of NE operating point K_i^* of G1, it is enough to prove that the L_i in (4) is quasiconcave function in x_i given $\mathbf{X}^{-i}$ on the convex set $\mathcal{X}_i = [x_i^{min}, x_i^{max}]$. The second order derivatives of L_i in (4) with respect to x_i is as follows:

$$\begin{aligned} \frac{\partial^2 L_i}{\partial x_i^2} &= -\frac{U_i}{(1+x_i)^2} - \frac{\psi_i}{(x_i - \rho_i \, x_i^{min})^2} \qquad (12) \\ &< 0, \forall x_i \in \mathcal{X}_i, \forall \, i \in \mathcal{I} \end{aligned}$$

Therefore, L_i is a strictly concave function on the compact convex set $\mathcal{X}_i$ and this implies that L_i is a quasiconcave function on $\mathcal{X}_i$. Henceforth, an NE point $\mathbf{K}^*$ exists. Also, as a result of strict concaveness, the unconstrained maximizer x_i^* is unique.

Due to paper space limit, the uniqueness of the NE Operating point and the Pareto Optimality Of The NE point of G1 are not included in this version of the paper. However, an extended version of the paper is available via e-mail when requested.

III. PERFORMANCE EVALUATION

We implemented in house simulator module consists of a TDD cell of one BS and several SSs. Our simulator is based on Nakagami-m channel model which is adopted to accurately describe the statistical variation of the channel gains between the BS and the SSs based on OFDM channel multiplexing.

Connections from each service class arrive following exponential distribution process with an exponential holding time as well. However, the packets arrival within each connection is implemented as a poisson process. For the connections' traffic model, we implemented part of the traffic model presented in [16], since it is specifically designed and tested for WiMAX simulation. This model implements VoIP traffic for the *ErtPS* class, video streaming traffic for the *rtPS* class, FTP traffic for the *nrtPS* class and background traffic for the BE class. Table I shows the traffic model used in simulation. Each simulation scenario is repeated 20 times.

The DL bandwidth is simulated as 20 MHz. The channel quality of each SS remains constant per frame, but is allowed to vary from frame to frame.

Nodes are placed in random over a simulation grid of 5000m×5000m. Number of subscriber stations are 1 to 30. Each subscriber station can have different types of connections at the same time; i.e. voice, video, FTP or background traffic.

TABLE I
TRAFFIC MODEL

Service	Traffic Type	MRTR	MSTR	ML	Packet (bytes)
ErtPS	Voice	12.5kbps	64kbps	80ms	60
rtPS	Stream video	64 Kbps	500 Kbps	150 ms	170-320
nrtPS	FTP	45 Kbps	500 Kbps	–	250
BE	Background	–	64 Kbps	–	250

The ratio of connections in the network, based on connection type, changes from 1 to 3. For example if the ratio is 1 : 1 : 1 : 1, then number of connections in the network for each type are equal. The frame size is fixed at a value of 10 ms equally divided between UL and DL traffic, the OFDM symbol duration is 12.5 μs, and the rate of frames is 100 frames/second. Time slots–which are directly related to OFDM symbols– are allocated for active flows at the beginning of each frame.

We evaluated the performance of the bandwidth provisioning algorithm by implementing a WiMAX schedular designed by same authors [17] at the connection level. We evaluate the performance of our algorithm referenced to the characteristics of a good bandwidth provisioning algorithm pointed out in the Introduction, Section I.

The performance of the algorithm is evaluated under lightly and heavy loaded network to study fairness and the enforcement of each class QoS requirements. Figure 1 shows the performance of the algorithm under light load. All traffic classes have a throughput higher than their minimum required number of time slots given that $\rho_i = 1$. Note that for all different classes, the class's average throughput is lower, when the mixture of connections is 1 : 1 : 1 : 1 or the percentage of that class connections is higher than other classes. This is due to the contention among same class connections for the class's time-slots. Figure 2 shows the average delay of the VoIP and Video traffic. Since the load is light the classes' average delay is much lower than their delay bound. We observe here that the packet loss is zero as well.

Figure 3 shows the results for the algorithm performance under heavy load network. Again the value of $\rho_i = 1$. The Figure shows that the algorithm is able to guarantee the QoS requirements of the different classes without starving the BE class. Additionally, we observe the same behavior of the average throughput when the percentage of a class connections is higher than the others or if it is equal. This is due to the same reason aforementioned.

In Figure 4, the delay of VoIP and Video is higher since the network is highly loaded. However, it does not exceed the delay bound of each class. We remark here that the algorithm delay performance is affected by the schedular implemented. However, the bandwidth provisioning algorithm controls the delay bounds through controlling number of class connections and the amount of time-slots allocated to the class above the class minimum requested number of time-slots. Figure 4 shows that the video has the lowest delay at the highest class connections percentage. This is because at this percentage the number of packet loss is the highest as shown in Figure 4(c); i.e. packets dropped are not included in calculating the average delay. Additionally, The packet loss of the Video traffic is higher than that of VoIP since the algorithm prioritizes the VoIP class over the Video class. Figure 5 shows the fairness among the different classes. Jain's index is used for studying fairness among classes. As shown in the figure the algorithm is able to provide fairness among the different classes. We did not include a figure for fairness among classes under lightly loaded network since the Jain's index was 1 for all scenarios.

IV. CONCLUSIONS

We presented a bandwidth provisioning algorithm to calculate for each class, the number of time-slots in a WiMAX frame required to meet the class connections QoS requirement. Our main contribution is designing a congestion based pricing algorithm to control congestion and provide for fairness among the different classes. Simulation revealed that the proposed algorithm is a good bandwidth provisioning algorithm since it has all the characteristics of a good bandwidth provisioning algorithm as defined in the Introduction. The bandwidth provisioning is designed to be a general algorithm irrespective of the underlaying technology as long as it is a frame based technology. The algorithm can be integrated to any scheduling scheme designed for WiMAX networks.

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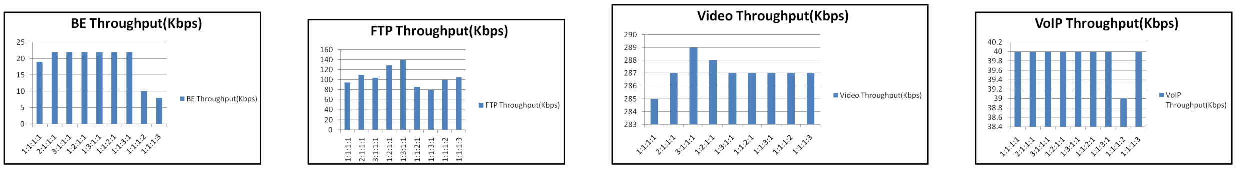
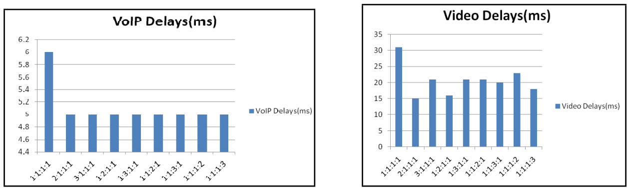


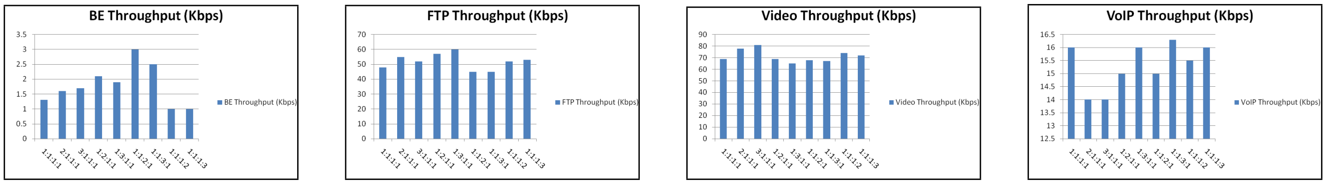
(a) BE Throughput in Kbps (b) FTP Throughput in Kbps (c) Video Throughput in Kbps (d) VoIP Throughput in Kbps

Fig. 1. Average Throughput in (Kbps) of (a)BE, (b)FTP, (c)Video and (d)Voice under Lightly Loaded Network



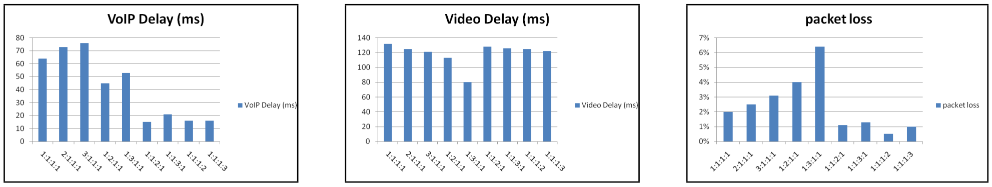
(a) Delay of VoIP Traffic in ms (b) Delay of Video Traffic in ms

Fig. 2. Average Delay in (ms) of (a)Video and (b)Voice under Lightly Loaded Network



(a) BE Throughput in Kbps (b) FTP Throughput in Kbps (c) Video Throughput in Kbps (d) VoIP Throughput in Kbps

Fig. 3. Average Throughput in (Kbps) of (a) BE, (b) FTP, (c) Video and (d) Voice under Heavy Loaded Network



(a) Delay of VoIP Traffic in ms (b) Delay of Video Traffic in ms (c) Packet Loss of Video Traffic

Fig. 4. Average Delay in (ms) of (a) Video and (b) Voice and (c) Packet Loss of Video under Heavy Loaded Network

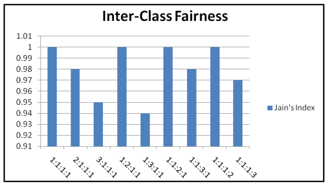


Fig. 5. Jain's Index Fairness Among FTP, Voice, Video and BE Connection Classes