Frame-Level Dynamic Bandwidth Provisioning for QoS-Enabled Broadband Wireless Networks

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Abstract

The increasing demand for wireless heterogeneous multimedia applications presents a real challenge to mobile service providers. Even with the substantial increase in the supported bandwidth in future broadband wireless systems such as 3.5G wireless cellular networks and 802.16 broadband wireless networks (WiMAX), these systems suffer from the same inherited problem in wireless networks, which is limited spectrum. Therefore, bandwidth provisioning is crucial for the success of such broadband wireless systems. In this paper, we propose a novel dynamic bandwidth provisioning scheme for broadband wireless communication. The proposed scheme spans multiple time slots/frames and optimally allocates them to the different classes of traffic depending on their weights, the real-time bandwidth requirements of their connections and their channel quality conditions. Simulation results show that satisfactions of different classes of traffic can be improved by implementing our scheme.

1. Introduction

Forecasts for emerging mobile device markets anticipate that bandwidth will be squeezed by applications like multimedia on demand. This will spur the need for data rates beyond what is offered by current wireless systems. To boost the support for such high data rates, new broadband wireless systems have been developed. For example, the 3rd Generation Partnership Project (3GPP) has standardized a 3.5G cellular system called High Speed Downlink Packet Access (HSDPA) [1] as an extension to the existing 3G Universal Mobile Telecommunications System (UMTS). HSDPA can theoretically support up to 14.4 Mbps, 7 times larger than the data rate offered by the UMTS. Another broadband wireless technology is WiMAX, which has been standardized by the IEEE 802.16 group [2]. WiMAX is a broadband wireless access network that could support up to 70 Mbps. The high data rates offered by these systems allow them to deliver a wide range of new broadband multimedia services such as streaming video and audio, mobile Internet browsing, high quality online gaming, and Voice over IP. Such services necessitate the support of different classes of service with widely different QoS requirements, which need to be guaranteed by wireless networks.

However, due to capacity limitations of wireless resources and high traffic demands, these systems require more careful and efficient resource management techniques in order to satisfy the QoS requirements of existing and new multimedia services and to maximize the system capacity at the same time.

Packet scheduling is one of the most important components of resource management that affects system capacity and potential QoS guarantees provided to mobile connections. A centralized downlink packet scheduler is implemented at the base stations of future broadband wireless systems to control the allocation of the downlink shared channels to the mobile connections by deciding which connection(s) should transmit during a given time frame. Therefore, packet scheduling can be thought of as a short-term resource sharing scheme since it only checks at the current time frame to make its decision.

In addition, to satisfy the QoS requirements of different applications in broadband wireless systems, packet scheduling must be coupled with a long-term resource sharing or bandwidth provisioning scheme that spans multiple time frames and decides how resources are shared among the different traffic classes and hence, their corresponding connections. The bandwidth provisioning scheme must divide the bandwidth or the corresponding time frames among different classes of traffic in an efficient, prioritized and fair manner.

Several downlink packet scheduling schemes have been proposed for future broadband wireless systems such as the ones in [3, 4, 5, 6]. These schemes utilize the information about the channel quality conditions of mobile connections in the scheduling decision to maximize the system capacity. In [7], we proposed a packet scheduling scheme that is able to simultaneously maximize the system capacity and achieve intra-class fairness.

Most of the work on bandwidth provisioning has been done at the admission level [8 ,9 ,10 ,11], where these schemes work as Call Admission Control (CAC) and aim at reducing the call blocking and dropping probabilities while satisfying the bandwidth requirements of different QoS classes. There is a need, however, for bandwidth provisioning at the frame level. This is due to the varying bandwidth requirements of mobile connections during their calls as a result of their traffic burstiness and also due to their varying channel quality

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conditions, which affect the capacity of the base station and hence, the amount of bandwidth that it can sustain to each one of them. Few works, have considered the problem of bandwidth provisioning at the frame level [12, 13, 14]. Nevertheless, none of which has considered the varying channel quality conditions of mobile connections. Hence they cannot achieve optimized bandwidth provisioning.

In this paper, we propose a frame-level dynamic bandwidth provisioning scheme to support QoS in broadband wireless systems. Our proposed scheme is designed to accommodate multi-class traffic with multiple connections having different bandwidth requirements. The main objective of the scheme is to determine the optimal number of time frames for each class of traffic in order to satisfy their long-term bandwidth requirements. The optimal number of frames for each traffic class is calculated based on the bandwidth requirements of its connections, their channel quality conditions and the weight of the class. Once the optimal number of frames is determined for each class; a packet scheduling scheme is utilized to determine the distribution of the assigned frames between the connections for each class.

The rest of this paper is organized as follows. Section 2 presents an overview of the proposed scheme. Section 3 provides a description of the proposed scheme. Performance results are shown in Section 4. Finally, conclusions drawn from the paper are given in Section 5.

2. Overview of Proposed Scheme

We consider a broadband wireless network with a cellular infrastructure, comprising a wired backbone and a number of base stations. The geographical area controlled by a base station is called a cell. In this paper, we design and implement our proposed scheme at a single-cell level. We assume that the base station serves *N* connections and selects a subset of them for transmission in a frame of some fixed time duration. We also assume that there are *K* classes of traffic, where class *i* has higher priority than class *i*+1, and $1 \le i$ and $i+1 \le K$. Let N_i denote the number of class *i* connections. Then $N = \sum_{i=1}^{K} N_i$. We consider connections within the same class can have different bandwidth requirements depending on the type of applications they are running. Suppose that the service provider wants to provision *SL* time frames between the *K* classes of traffic to satisfy their long-term bandwidth requirements. We assume that *SL* is given. The proposed scheme works as follows. First, the bandwidth provisioning scheme, which decides the partition of *SL* among the *K* classes of traffic based on the bandwidth requirements of their connections, their channel quality conditions and their priorities. Once each class is assigned a number of frames, a packet scheduling algorithm is employed to schedule connections within each class based on these frames. Therefore, the bandwidth provisioning scheme is executed every *SL* frames whereas packet scheduling algorithm is executed every frame as shown in Figure 1. In the next section, we present the details of the proposed scheme.

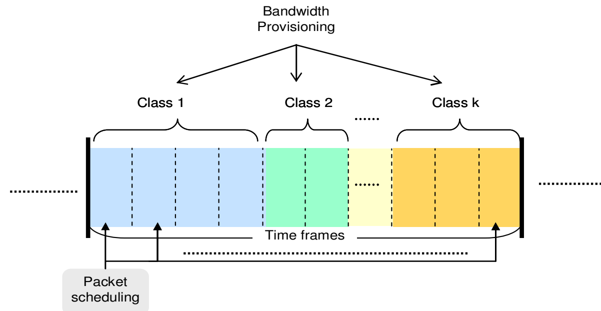

Figure 1. Scheme Overview

3. The Proposed Dynamic Bandwidth Provisioning

We distinguish two cases of bandwidth provisioning: In the first no bandwidth guarantee is required for any service class. Then we extend our scheme to support minimum bandwidth guarantees.

A. Basic Bandwidth Provisioning

Before proceeding with describing the proposed bandwidth provisioning scheme, we make the following definitions:

- S_{ij} : the required bandwidth of connection *j* of class *i*, j = 1, ..., N_i
- SL_i : number of frames assigned to class *i*.
- $\overline{R_i}(t)$: effective average estimated data rate (per second) that the base station can transmit at to the connections of class *i* during the next *SL* frames. This data rate will depend on the estimated instantaneous channel quality conditions of the connections. $\overline{R_i}(t)$ can be computed using a moving average (i.e., $\overline{R_i}(t) = \alpha \cdot \overline{R_i}(t-1) + (1-\alpha) \cdot R_i(t)$) or using channel predictions schemes proposed in [15], [16] and [17].
- B_i : total required bandwidth per frame of all connections in class *i* at the beginning of the *SL* frames. Let $\sum_{j=1}^{N_i} S_{ij}$ = the total required bandwidth per second of all connections in class *i* and let D_{frame} be the frame duration in second, then $B_i = \left(\sum_{j=1}^{N_i} S_{ij} / 1 / D_{frame} \right)$. That is, B_i determines how much the required transmission rate base station should be sending at per frame in the next *SL* frames in order to satisfy the connections of class *i*.
- $\overline{B_i} = \left((\overline{R_i}(t) / (1 / D_{frame})) \right)$: actual (i.e., effective) total transmitted bit rate per frame for connections in class *i*. That is, $\overline{B_i}$ determines the actual transmission rate per frame of the base station in the next *SL* frames for the connections of class *i*.

To satisfy all connections, the base station should assign $SL * B_i$ bandwidth per SL frames. However, this may not be possible in practice due to the high demand of applications that require high bandwidth allocations and also due to the limitations of the base station's capacity, which is determined by the channel quality conditions of the mobile connections. Therefore, the main objective of our bandwidth allocation scheme is to divide the SL frames between the K classes of traffic such that $\sum_{i=1}^{K} SL_i = SL$ and the satisfaction of different classes of traffic is maximized. To do so, our bandwidth provisioning scheme will divide the SL frames between the K classes of traffic such that it maximizes $\frac{SL_i * \overline{B_i}}{SL * B_i}$ (i.e. the ratio between the requested bandwidth of class i connections given that SL_i frames are assigned to class i to the bandwidth that the base station should transmit at during SL frames to satisfy the maximum bandwidth requirements of class i). The frames assigned to class i (i.e., SL_i) should guarantee that no class of traffic is assigned more than its maximum required bandwidth (i.e., $SL_i * \overline{B_i} \le SL * B_i^{\max}$).

To summarize, in our bandwidth allocation scheme, the following optimization problem will be solved:

Objective: $$\max_{SL_i, 1\le i\le K} \sum_{i=1}^{K} w_i \left(\frac{SL_i * \overline{B_i}}{SL * B_i} \right)$$

Subject to:

$$\sum_{i=1}^{K} SL_i = SL \text{, and}$$

$$SL_i * \overline{B_i} \le SL * B_i^{\max} \quad (1)$$

Where w_i is a weight assigned to class i to give it priority over class i+1 in the frame assignment process. Therefore, the weights in our bandwidth provisioning scheme can be used to determine the appropriate level of inter-class fairness (i.e., fairness between different classes) according to the requirements of the service providers. The proposed bandwidth allocation scheme is adaptive to the varying requirements of different classes since the objective function is evaluated every SL frames and, therefore, if the required bandwidth (or frames) for class i changes during the current SL frames (due to new admitted connections, completed connections, and/or traffic burstness), its new total required bandwidth will be reflected in the next SL frames.

B. Long-Term Bandwidth Provisioning with Minimum Guaranteed Bandwidth

Even though the dynamic bandwidth provisioning scheme in Section III.A aims at maximizing the satisfaction of the different classes of traffic, it does not provide any bandwidth guarantees to any class. The service provider may want to provide such guarantees to certain classes and, therefore, the bandwidth provisioning scheme should consider such a case. Here, we extend our scheme to support minimum bandwidth guarantees. Let:

- $S_{ij}^{\min}$: minimum required bandwidth of connection j of class i.
- $B_i^{\min}$: total required minimum bandwidth per frame of all connections in class i at the beginning of the SL frames. Therefore, $B_i^{\min} = \left(\sum_{j=1}^{N_i} S_{ij}^{\min} / 1 / D_{frame} \right)$.

In this case, the frames will be assigned such that they satisfy two constraints; the minimum bandwidth constraint (i.e., $SL * B_i^{\min} \le SL_i * \overline{B_i^{new}}$) and the required bandwidth constraint (i.e., $SL_i * \overline{B_i^{new}} \le SL * B_i$) where $\overline{B_i^{new}}$ is the same as the one in pervious section.

Therefore, the bandwidth provisioning problem becomes:

Objective: $$\max_{SL_i, 1\le i\le K} \sum_{i=1}^{K} w_i \left(\frac{SL_i * \overline{B_i}}{SL * B_i} \right)$$

Subject to:

$$\sum_{i=1}^{K} SL_i = SL \text{, and}$$

$$SL * B_i^{\min} \le SL_i * \overline{B_i} \le SL * B_i^{\max} \quad (2)$$

C. Short-Term Packet Scheduling Scheme

Once each class is assigned a number of frames, these frames will be shared among connections within each class according to the packet scheduling scheme, which is executed every time frame. These frames can be served in any order. For example, they could be served based on the delay or packet loss requirements of the traffic classes. In this paper, however, the frames of the class with the highest priority are served first, then those of the class of the second highest priority, etc. We utilize a packet scheduling scheme that we proposed in [7], though our proposed dynamic bandwidth provisioning scheme can utilize any other packet schedulers. This scheduler is used because it has been shown to increase the system capacity and provide intra-class fairness simultaneously [7].

4. Performance Evaluation

In this section, we evaluate the performance of our proposed scheme by means of dynamic discrete event simulation. We tested our scheme on HSDPA system. As aforementioned, HSDPA is a 3.5G wireless system that has been introduced by the 3GPP as an extension to the 3G UMTS [1].

A. Simulation Model

For simplicity, we simulated one-cell and ignored handoffs. The base station is located at the center of the cell. The cell radius is 1 Km. Two classes of traffic are considered (i.e. K=2), streaming and interactive classes. Streaming connections request one of two types of applications, video and audio streaming. Video streaming connections require a data rate of 128 Kbps whereas audio streaming connections require a data rate of 32 Kbps. These data rates are chosen from within the range of specific bandwidth requirements defined by WCDMA in order to provide adequate service to mobile connections [18]. For demonstration purposes, we assume that video streaming has more priority than audio streaming[1]. Therefore, we set the parameters in our scheduler [7] differently for these two services in order to prioritize between them. The interactive class has one application which is FTP. Each FTP user sends a request for one FTP file and requires a data rate of 128 Kbps and then terminates after the download is complete. It should be noted that we chose this data rate to test the ability of our proposed scheme to serve two different applications that belong to two different classes and request the same data rate. All simulation parameters regarding traffic generation and channel model can be found in [7].

We choose SL=20 time frames (i.e. 20 x 2ms) and we use a moving average to compute $\overline{R_i(t)}$ (i.e., $\overline{R_i}(t) = \alpha \cdot \overline{R_i}(t-1) + (1-\alpha) \cdot R_i(t)$ with $\alpha = 0.99$). We adopt the same channel model as in [7]. The simulation time step is one time frame, which is 2 ms (i.e., the time frame of HSDPA [1]), and the simulation time is 200 s.

B. Test Cases and Performance Metrics

We evaluate the performance of our proposed scheme under two cases. In the first case, we always serve class 1 connections as long as they have packets to send (i.e., we give strict priority to class 1 over class 2). In this case, there is no need for bandwidth provisioning and, therefore, only the packet scheduling scheme is utilized. In the second case, we give class 1 higher but not strict priority over class 2 by giving it a higher weight than class 2. Therefore, we use our bandwidth provisioning scheme in this case along with the packet scheduling. Pedestrian A (Ped A) environment [19] is used in the simulation. Mobile connections in Ped A environment move at a fixed speed of 3 Km/hr, which is the recommended value by the 3GPP. We use the following performance metrics to evaluate the performance of the proposed scheme:

- Percentage of assigned frames to each class: the total number of frames assigned to class i divided by the total number of assigned frames. We use this performance metric to measure fairness between classes (i.e. inter-class fairness).
- Jain Fairness Index (JFI): a fairness index used to calculate fairness among connections that belong to the same class and have the same bandwidth requirements (i.e. intra-class fairness). Let $\overline{S^z{}_{ij}(t)}$ be the average bandwidth for connection z in class i, then the JFI is calculated as follows [20]:

$$JFI = \frac{\left(\sum_{z=1}^{N_{ij}} \overline{S^z{}_{ij}(t)}\right)^2}{N_{ij} \sum_{z=1}^{N_{ij}} (\overline{S^z{}_{ij}(t)})^2}, \quad \overline{S^z{}_{ij}(t)} \geq 0 \ \ \forall z \tag{3}$$

where N_{ij} is the number of connections in class i, which request the same bandwidth. Note that if all such connections have the same average bandwidth, then JFI=1. Lower JFI values indicate that connections have high variances in their average bandwidth, which reveals unfairness in distributing the wireless resources among the connections according to this scheme.

- Percentage of connection satisfaction: percentage of connections, which receive average bandwidth that is larger than or equal to 75% of their requested bandwidth.

C. Simulation Results

Figure 2 depicts percentage of frames assigned to classes 1 and 2 for different total arrival rates to the system in case of strict priority. As the figure shows, class 1 is assigned most of the frames (above 80%) even when the total arrival rate is low (e.g. 0.1). In fact, when the total arrival rate is larger than 0.7, all the frames are assigned to class 1 and none is assigned to class 2. This behavior is expected with strict priority since class 2 is only served when class 1's connections have no packets to send regardless of the requirements of class 2, which results in inter-class unfairness. However, our bandwidth provisioning scheme can improve inter-class fairness since it considers the requirements of both classes and assigns the frames accordingly. This is confirmed in Figure 3, which shows that by using our bandwidth provisioning scheme more frames are assigned to class 2 to increase its share of the bandwidth. The bandwidth share between the two classes is further enhanced by increasing the weight of class 2 to 3 as shown in Figure 4. Therefore, the weights in our bandwidth provisioning scheme can be set to determine the appropriate level of inter-class fairness according to the requirements of the service providers.

The Jain Fairness Index for each traffic type (i.e., video, audio and FTP connections) in case of strict priority is shown in Figure 5. As aforementioned, the Jain Fairness Index is used to test inter-class fairness. The figure shows that both classes of traffic achieve relatively good inter-class fairness because of the effect of the intra-class fairness measure in our scheduler [7], which forces it to serve connections as they tend to get low average bandwidth compared to their requested ones. When the total arrival rate to the system is larger than 0.7, the Jain Fairness Index of FTP connections is undefined because class 2 is assigned zero time frames as shown in Figure 2. In addition, Figure 6 shows that the connections of class 1 achieve slightly higher fairness index than the connections of class 2 is because more frames are assigned to class 1 as mentioned earlier and hence, there is not enough time for our intra-class fairness measure [7] to make an impact. This is shown clearly in Figure 6, which depicts the Jain Fairness Index o for each traffic type with our bandwidth provisioning scheme. In this case, more frames are assigned to class 2 (i.e.

[1] This is possible in the streaming class depending on the requirements of users and how much money they are willing to pay for the service. In the conversational class however, audio or voice should have higher priority.

FTP traffic) and, therefore, we can see that its fairness index approaches those of video and audio traffics.

Percentage of satisfied connections for each traffic type with strict priority is shown in Figure 7. We can see that video streaming connections are more satisfied than audio streaming connections since they have more priority. Also, as the number of class 2 connections increases, their satisfaction rapidly decreases until it reaches zero. This means that those connections still get some data rates (hence the relatively good level of fairness in Figures 5 and 6). However, their data rates are not enough to classify them as satisfied according to our definition of connection satisfaction. Figure 8 shows the percentage of satisfied connections for each traffic type when our bandwidth provisioning scheme is used. This figure shows that we can increase the satisfaction of class 2 connections at a slight decrease in satisfaction of class 1 connections if we use the proposed bandwidth provisioning scheme.

5. Conclusions

Future broadband wireless systems will enhance the mobile connections wireless experience by supporting a wide range of multimedia applications. However, to satisfy the QoS requirements of the supported multimedia applications and maximize the system capacity, these systems require effective resource management schemes. In this paper, a novel frame-level dynamic bandwidth provisioning scheme in broadband wireless network is proposed. The proposed scheme allocates the optimal number of time frames between different classes of traffic in a prioritized way such that it satisfies their long-term QoS. Once the optimal number of frames is assigned to each class, packet scheduling distributes the frames in a fair and efficient way to connections within one class.

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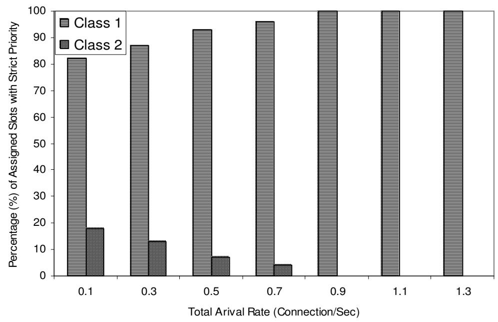

Figure 2. Percentage of assigned frames with strict priority

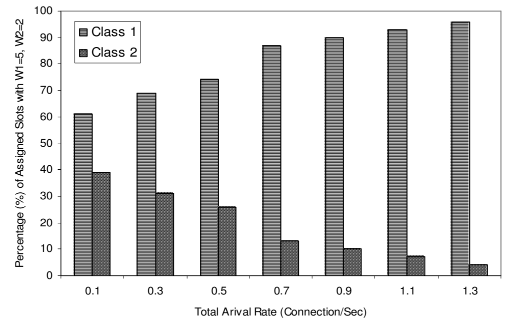

Figure 3. Percentage of assigned frames with bandwidth provisioning and $w_1 = 5$ and $w_2 = 2$

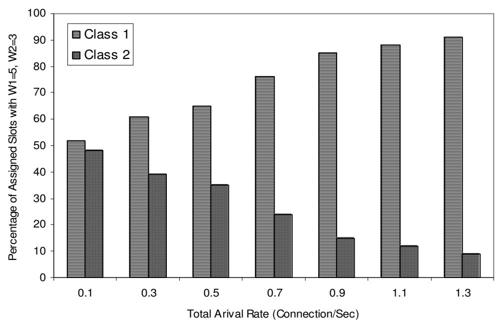

Figure 4. Percentage of assigned frames with bandwidth provisioning and $w_1 = 5$ and $w_2 = 3$

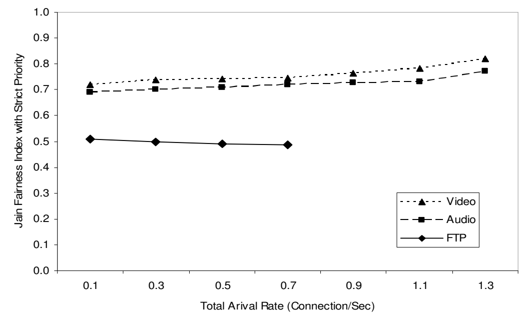

Figure 5. The Jain Fairness Index with strict priority

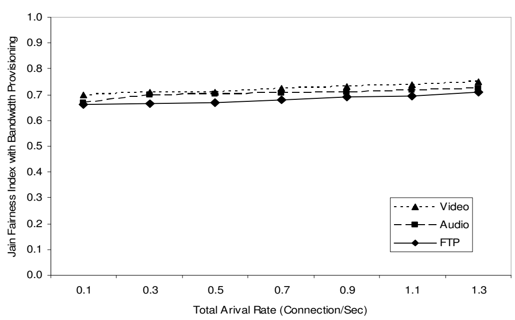

Figure 6. The Jain Fairness Index with bandwidth provisioning

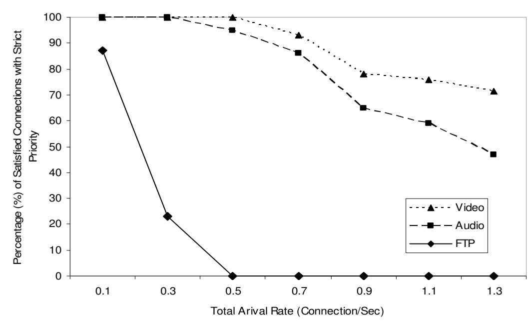

Figure 7. Percentage of satisfied connection with strict priority

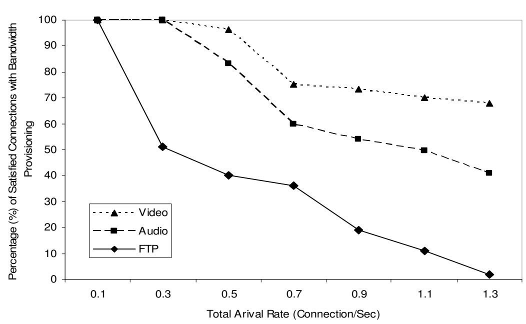

Figure 8. Percentage of satisfied connection with bandwidth provisioning