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Abstract

Scheduling is an essential mechanism in IEEE 802.16 networks for distributing the available bandwidth among the active connections so that their quality of service requirements can be furnished. Scheduling mechanisms adopted in wired networks, when used in wireless networks lead to inefficient use of the bandwidth since the location dependent and time varying characteristics of the wireless link usually are ignored by the wired networks. This paper introduces a standard-compliant cross-layer scheduling mechanism which considers the modulation and coding scheme of each mobile station to increase the efficiency of channel utilization while furnishing the QoS requirements of the connections.

1 Introduction

To provide Quality of Service (QoS) for stationary and mobile users, the IEEE 802.16 standard [4], also known as WiMAX (Worldwide Interoperability for Microwave Access), and its amendment, the IEEE 802.16e [5], define five types of service flows and mechanisms for bandwidth requests by the connections in the uplink direction. The Unsolicited Grant Service (UGS) periodically receives fixed size grants without the need to request them. The extended real time Polling Service (ertPS) uses a grant mechanism similar to the one used to support UGS connections, but periodically allocated grants can be used to send bandwidth requests to inform the required grant size. The real-time Polling Service (rtPS) offers periodic unicast bandwidth request opportunities to subscribers; these opportunities ensure latency bound and minimum traffic rate guarantees. The non-real-time Polling Service (nrtPS) provides periodic unicast bandwidth request opportunities, but using more

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spaced intervals than rtPS, as well as minimum rate guarantee. The Best Effort (BE) shares contention bandwidth request opportunities with the nrtPS service flow. Specific scheduling mechanisms for the support of these classes of service are left for vendors to implement in their own products.

Scheduling mechanisms have been widely investigated for wired networks, however, wireless systems pose extra challenges to the development of this mechanism due to the wireless link characteristics, such as, time and location-dependent, signal attenuation and fading. To increase efficiency, several techniques have been employed, such as smart antennas, MIMO, and adaptive modulation and coding (AMC) technique. The scheduler, therefore, needs to be designed to work with these techniques. The AMC technique adapts modulation and coding to have transmissions with better quality under different conditions of the wireless channel. The scheduling mechanism needs to consider such adaptive scheme.

Borin and Fonseca [7, 8, 9] proposed standard-compliant scheduling solutions for the uplink traffic in IEEE 802.16 networks which supports; however, they do not consider the conditions of the wireless channel. An extension presented in [6] proposes an uplink scheduler that takes into account the quality of the signal by blocking the transmission of mobile subscriber stations (MSSs) experiencing a low average SNR value.

This paper extends the scheduler proposed in [6], so that bandwidth allocation decisions also take into account information on current modulation and coding scheme (MCS) used by mobile users. Moreover, AMC techniques are considered. In this way, the conditions of the wireless channel of each MSS are estimated more accurately and, as result, the network resources are used more efficiently.

Simulation results show that the proposed approach improves the network performance in suburban areas without affecting the QoS provision required by the IEEE 802.16 standard.

The rest of this paper is organized as follows. Section 2 discusses related work. Section 3 describes the channel model and physical layer considered in this paper. Section 4 presents the proposed scheduling mechanism. Section 5 describes the simulation environment used to evaluate the scheduler. Section 6 presents numerical results and Section 7 concludes the paper.

2 Related work

Due to characteristics such as location-dependent and time-varying wireless link capacity, scheduling algorithms developed for wired networks may lead to low performance when used in wireless networks. An overview of several scheduling mechanisms developed for wireless networks is presented in [20] and in [2]. However, none of them is able to support the QoS requirements of the five types of service flow defined by the IEEE 802.16e standard[5].

Schedulers can use different metrics to estimate the channel condition. In [1], the channel quality is measured by the signal-to-noise ratio (SNR), while in [15, 17], and [16] it is estimated using the instantaneous transmission rate. Nevertheless, those works focus on downlink scheduling.

Although both downlink and uplink schedulers need to provide QoS requirements, the uplink scheduler is more complex since it does not have direct access to the connections queues. The uplink scheduler depends on the bandwidth requests sent by the mobile stations in order to keep information on each connection status. Such requests may suffer delays, generated by the contention mechanism, for example, or may be lost due to channel noise resulting in delivering outdated info.

In [3], the authors present a fair uplink scheduler based on TCP timeout and congestion window values and on the channel conditions. However, it does not consider the real time service classes. In [19], the proposed cross-layer scheduler works together with a mechanism which adjusts dynamically the size of the uplink and of the downlink subframes according to the network conditions. The evaluation of the proposed mechanism does not consider realistic applications.

In [18], it is introduced a set of algorithms for the BS to allocate channels/slots to different MSSs in an IEEE 802.16 OFDMA/TDD network, but the authors do not evaluate the delay performance for maximum latency requirement for their proposal.

In order to guarantee latency requirements for real time applications, the scheduling mechanism proposed in [15] classifies packets in four classes based on the history of packets delays. The scheduler uses an opportunistic approach to give higher priority to mobile stations with better channel conditions. However, this proposal fails to provide minimum rate guarantees.

In [11], it is proposed a two-stage cross-layer QoS support framework with an uplink scheduling algorithm which assigns priority values to the connections based on the service class priority, the quality of the channel, the delay of the packets and the status of the queue. The performance evaluation of the proposed scheduler does not consider the Best Effort service.

The present work proposes a cross-layer standard-compliant scheduler for the uplink traffic in IEEE 802.16e networks which takes into account the link adaptation by the mobile stations. Different from previous works, the evaluation of the proposed solution includes all the five types of service defined in the standard as well as realistic traffic models for each type of service. The propagation model used in this paper to simulate a suburban environment for IEEE 802.16 networks is also realistic. Moreover, most of previous work focus on the downlink scheduler and do not consider all seven modulation and coding profiles defined in the standard.

3 Channel and physical layer model

This work uses the OFDM PHY layer model and the COST 231 Hata Propagation Model [12] to simulate the channel of an IEEE 802.16 network in a suburban environment. Although the channel operates in the 500MHz to 2000MHz frequency range, the empiric model has low execution complexity and uses correction factors for suburban, urban, and rural environments.

Based on the distance between the antenna of the base station (BS) and the receiver of the MSS, the channel model estimates a path loss value and, hence, computes the signal to noise ratio (SNR) of each packet arriving at the receiver. Depending on the loss probability

Table 1: WiMAX OFDM Profiles

Modulation and Code Scheme	Efficiency (bits/symbol)	Threshold (dB)
BPSK 1/2	0.5	1.0
QPSK 1/2	1.0	5.9
QPSK 3/4	1.5	12.2
16QAM 1/2	2.0	17.6
16QAM 3/4	3.0	21.8
64QAM 2/3	4.0	51.7
64QAM 3/4	4.5	68.2

for the modulation being used, the packet can be dropped due to errors. Therefore, the larger the distance between the BS and the MSS, the higher is the packet loss ratio and the lower is the MSS goodput. In order to use the physical layer information, the BS calculates the average SNR of the packets received from each MSS. The average SNR value is calculated using the Exponential Weighted Moving Average (EWMA) method.

The OFDM channel used in this paper supports the Adaptive Modulation and Coding (AMC) mechanism which enables fine tuning of the PHY parameters to optimize the system performance and to reach the desired packet error rate (PER). The IEEE 802.16 standard does not define which rate adaptation mechanism should be used, neither the SNR values for each modulation and code scheme. For simplicity, in this paper, modulation is changed when the SNR value reaches pre-defined thresholds calculated in a previous simulation. Therefore, the average SNR reflects the modulation being used by an MSS. The modulation and code scheme (MCS) profiles as well as the efficiency of each scheme, defined by the standard, and the thresholds values are described in Table 1.

4 Scheduling mechanism

The scheduler proposed in this paper is fully-standard compliant and supports the *maximum latency*, *minimum reserved traffic rate*, *maximum sustained traffic rate*, and *maximum traffic burst* requirements. It uses three priority queues, with low, intermediate, and high priorities. The lowest priority queue stores BE bandwidth requests while the intermediate queue stores rtPS and nrtPS bandwidth requests. The highest priority queue stores UGS and ertPS periodic data grants as well as unicast requests opportunities. Requests can be migrated to the highest priority queue to support the *minimum reserved traffic rate* and *maximum latency* requirements as well as to allocate bandwidth to BE connections if bandwidth is available at the current frame. The scheduler creates an UL-MAP message to grant bandwidth slots to the connections at the highest priority queue after migration.

UGS and ertPS grants for data transmission, and rtPS and nrtPS unicast opportunities for bandwidth request transmission are generated periodically and are inserted in the highest priority queue as specified in the standard.

The *maximum latency* requirement of rtPS connections is guaranteed for those connections that did not receive the *minimum reserved traffic rate* in a time window of duration T. Given a *minimum reserved traffic rate*, backlogged requests, and traffic rate received in the current window, a priority value is assigned to the request so that those with larger backlog obtain high priority.

Moreover, to ensure that connections do not violate the *maximum sustained traffic rate* and *maximum traffic burst*, a dual leaky bucket is used.

To increase overall efficiency under a certain wireless channel condition, those MSSs with the most efficient modulation are chosen by the scheduler. Moreover, before scheduling bandwidth requests, the scheduler adjust the MSSs modulation and coding schemes according to their MCS profiles (Table 1) and the estimated SNR value.

ALGORITHM *Scheduling*

1. insert, in the high priority queue, the periodic data grants and unicast request opportunities that must be scheduled in the next frame;
2. *CheckDeadline;*
3. *CheckMinimumBandwidth;*
4. *DistributeFreeResources;*
5. schedule the requests in the high priority queue starting from the head of the queue;

The Algorithm *Scheduling* presents the proposed solution. The scheduler is executed at each frame. First, periodic grants are enqueued at the highest priority queue. Then, those with bandwidth deficit are served followed by the regular requests of rtPS and nrtPS classes. Finally, the BE connections are served.

In the *CheckDeadline* procedure (lines 1-7), the rtPS requests with expiring deadline are migrated to the highest priority queue.

The *CheckMinimumBandwidth* procedure (lines 8-26) migrates rtPS and nrtPS requests from the intermediate queue to the high priority queue. The deficit to the minimum bandwidth requirement is taken into account as well as the quality of the MSSs transmission since those with better condition consumes less bandwidth at a frame. The priority of a request is computed taking into account these two parameters. In this way, connections with high channel quality and with bandwidth deficit are assigned to highest priority values.

The *DistributeFreeResources* procedure (lines 27-30) distributes the available bandwidth for BE connections in a First-Come First-Served (FCFS) fashion. This procedure avoids bandwidth starvation in case the MSS stays with a low channel quality for a certain period.

5 Simulation Experiments

The scheduler proposed in this paper was implemented in an IEEE 802.16 module for the ns-3 simulator [10].

The simulated network uses a point-to-multipoint topology with a centralized BS and the MSSs distributed around it. The MSSs are uniformly distributed around the base station in a circle with 1600 meter of radius.

The physical layer uses OFDM technology with 7 profiles defined by the IEEE 802.16 standard for data packets transmission and BPSK 1/2 modulation and coding for signaling packets transmission. The distance between the MSSs and the BS always guarantees that management packets are not lost. The frame duration is set to 5 ms with 1:1 downlink-to-uplink TDD split. To eliminate the impact of packet scheduling at the MSSs on uplink scheduling, each MSS has only one uplink service flow.

In the simulated scenario, we consider different types of traffic: FTP traffic for BE and nrtPS service. Voice and voice with silence suppression associated with UGS and ertPS services, respectively, and video traffic for rtPS service.

The voice model used was an exponential "on/off" model with mean duration of the "on" and "off" periods equals to 1.2 s and 1.8 s, respectively. During the "on" periods, 66-byte packets are generated at every 20-ms [13]. The voice with silence suppression model used Enhanced Variable Rate Coded (EVRC) [21], with packets generated every 20 ms employing Rate 1 (171 bits/packet), Rate 1/2 (80 bits/packet), Rate 1/4 (40 bits/packet) or Rate 1/8 (16 bits/packet). Video traffic was generated by real MPEG-4 traces [14] encoded at a low quality level. Sixty-minutes long videos with bit rate varying from 35 Kbps to 188 Kbps were used in the simulations. FTP traffic and CBR traffic were 500 Kbps transmission rate and 512 packet size generated.

The unsolicited grant interval for UGS and for ertPS is 20 ms. The unsolicited polling interval for the rtPS service is 100 ms and for the nrtPS service is 1 s.

The maximum latency requirement of the rtPS service is 400 ms and each connection has its own minimum reserved traffic rate and maximum sustained traffic rate requirements (which vary according to the mean rate of the transmitted video). The nrtPS service has minimum reserved traffic rate requirement of 250 Kbps and maximum sustained traffic rate requirement of 750 Kbps. The BE service does not have QoS requirement. In the experiments, it is assumed that the sum of the minimum bandwidth will not exceed the channel capacity.

Simulation experiments run for 3600 seconds. To produce each result, simulations were run ten times with different seeds. The mean values and the confidence intervals with 95% confidence level are shown in the figures.

6 Numerical Results

This section discusses the results found in the simulations for the described scenario. For the sake of comparison, the described scenario was also simulated using the MBQoS (Migration-Based Scheduler for QoS provisioning) approach [9], which does not consider the conditions of the wireless channel.

The proposed scheduler gives higher priority to those MSSs with most efficient modulation and coding scheme since they occupy the channel for shorter period than those with more robust modulation and coding scheme.

In the simulated scenario, the number of MSSs increases from 5 to 75 in steps of 5 units (one for each type of service). These experiments aim at assessing the benefits of the proposed cross-layer approach as well as whether or not the proposed scheduler is able to guarantee the maximum latency requirements of the rtPS connections.

Figures 1, 2, and 3 show the mean goodput for the nrtPS, rtPS and BE classes, respectively. Under low loads, both the opportunistic and the non-opportunistic approaches produce similar goodput values for the nrtPS connections, since all nrtPS bandwidth requests are served. Under high loads, the size of the intermediate queue increases and the scheduler is able to serve only the requests with highest priority values at each frame. By considering not only the bandwidth demand, but also the channel quality of the connections when assigning the priority values, the Opportunistic MBQoS scheduler is able to reduce the bandwidth waste at each frame, thus, producing higher goodput values for the nrtPS connections than does the MBQoS scheduler. Moreover, when there are 15 nrtPS connections, the non-opportunistic approach is not able to provide the minimum traffic rate requirement (250 Kbps).

Since for real time applications packets that arrive late at the destination are useless, the Opportunistic MBQoS always migrate to the high priority queue the rtPS requests whose deadline is approaching, independently on the channel conditions of the correspondent MSS. Therefore, the rtPS connections have similar goodput results for both evaluated schedulers, as can be seen in Figure 2.

The BE service does not have QoS requirements, which explains the sharp decrease of the goodput for the BE connections (Figure 3). There is not much difference between the performance of both schedulers, i.e., the opportunistic scheduler does not penalize the BE connections more than the non-opportunistic scheduler.

Figure 4 shows that both schedulers were able to provide the maximum latency requirement of 400 ms for the rtPS connections. As previously mentioned, the Opportunistic MBQoS scheduler serves rtPS requests when their deadline is approaching, even if the channel quality of the MSS is not good, consequently, the average latency of the rtPS connections was similar for both schedulers.

The goodput values of the UGS and of the ertPS connections were not affected by the increase of the number of MSSs. As can be seen in Figure 5, the uplink scheduler is able to provide data grants at fixed intervals as required by the standard. Since periodic grants are allocated independently of the channel conditions, the Opportunistic MBQoS scheduler did not enhance the results obtained with the MBQoS scheduler.

Figure 6 evinces that the use of the cross-layer approach provides channel utilization 10% higher than the non-crosslayer approach. In other words, with the same amount of physical symbols, the proposed scheduler is able to improve the goodput in the uplink direction. This is consequence of assigning high priority values to the MSSs with more efficient modulation and coding scheme.

7 Conclusions

This paper introduced a standard-compliant cross-layer uplink scheduler for IEEE 802.16 networks which supports adaptive modulation and coding scheme. In order to improve bandwidth usage, the proposed scheduler assign high priority values for mobile stations using the most efficient modulation and coding scheme profiles.

Simulation results show that the proposed approach increases the uplink subframe utilization compared to a non-crosslayer approach when rtPS and nrtPS connections are present. For UGS, ertPS, and BE connections, both schedulers provide similar goodput and latency values. From the service provider perspective, an increase in the bandwidth utilization represents the possibility of serving a higher number of clients. The joint use of the proposed scheduler with a connection admission control mechanism will be investigated in future work.

References

[1] A. Iera, A. Molinaro, S. Pizzi, and R. Calabria, *Channel-aware scheduling for QoS and fairness provisioning in IEEE 802.16/WiMAX broadband wireless access systems.* IEEE Network, vol. 21, no. 5, pp. 34-41, 2007.

[2] H. Fattah and C. Leung, *An overview of scheduling algorithms in wireless multimedia networks.* IEEE Wireless Communications, vol. 9, no. 5, pp. 76-83, 2002.

[3] H. K. Rath, A. Karandikar, and V. Sharma, *Adaptive modulation-based TCP-aware uplink scheduling in IEEE 802.16 networks.* Proceedings of the IEEE International Conference on Communications, pp. 3230-3236, 2008.

[4] IEEE Standard 802.16-2004, Part 16. *Air Interface for Fixed Broadband Wireless Access Systems*, 2004.

[5] IEEE Standard 802.16-2005, Part 16. *Air Interface for Fixed and Mobile Broadband Wireless Access Systems*, 2005.

[6] F. A. Kubota, J. F. Borin, and N. L. S. da Fonseca, *Cross-layer Uplink Scheduler for the IEEE 802.16 standard*, Proceedings of the IEEE Global Telecommunications Conference - GLOBECOM, pp. 1-6, 2010. DOI `http://dx.doi.org/10.1109/GLOCOM.2010.5683331`.

[7] J. Freitag, and N. L. S. Fonseca, *Uplink Scheduling with Quality of Service in IEEE 802.16 Networks.* In Proceedings of the IEEE Global Telecommunications Conference - GLOBECOM, pp. 2503-2508, 2007. DOI `http://dx.doi.org/10.1109/GLOCOM.2007.476`

[8] J. F. Borin, and N. L. S. Fonseca, *Scheduler for IEEE 802.16 networks.* IEEE Communications Letters, vol. 12, no. 4, pp. 274-276, 2008. DOI `http://dx.doi.org/10.1109/LCOMM.2008.072110`

[9] J. F. Borin, and N. L. S. Fonseca, *Uplink Scheduler and Admission Control for the IEEE 802.16 Standard.* In Proceedings of the IEEE Global Telecommunications Conference - GLOBECOM, pp. 1-6, 2009. DOI `http://dx.doi.org/10.1109/GLOCOM.2009.5425779`

[10] J. Farooq and T. Turletti, *An IEEE 802.16 WiMAX Module for the NS-3 Simulator.* Proceedings of the Second International ICST Conference on Simulation Tools and Techniques, pp. 1-11, 2009.

[11] J. Lu and M. Ma, *A cross-layer elastic CAC and holistic opportunistic scheduling for QoS support in WiMAX.* Computer Networks, vol.1155-1168 , no. 7, pp. 1155-1168, 2010.

[12] M. Hata, *Empirical formula for propagation loss in land mobile radio services.* IEEE Transactions on Vehicular Technology, vol. 29, no. 3, pp. 317-325, 1980.

[13] P. Brady, *A model for generating On-Off speech patterns in Two-Way conversations.* Bell System Tech. Journal, vol. 48, pp. 2445-2472, 1969.

[14] P. Seeling, M. Reisslein, and B. Kulapala, *Network Performance Evaluation Using Frame Size and Quality Traces of Single-Layer and Two-Layer Video: A Tutorial.* IEEE Communications Surveys and Tutorials, vol. 6, no. 2, pp. 58-78, 2004.

[15] Q. Ho, M. Ashour, and T. Le-ngoc, *Delay-sensitive and channel-aware scheduling in next generation wireless networks.* Proceedings of the Canadian Conference on Electrical and Computer Engineering, pp. 1801-1804, 2008.

[16] Q. Liu, X. Wang, and G. B. Giannakis, *Cross-Layer Scheduler Design with QoS Support for Wireless Access Networks.* Proceedings of the International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks, pp. 21-29, 2005.

[17] R. Ghazizadeh, P. Fan, and Y. Pan, *A two-layer channel-aware scheduling algorithm for IEEE 802.16 broadband wireless access systems.* Journal of Applied Sciences, vol. 9, no. 3, pp. 449-458, 2009.

[18] V. Singh and V. Sharma, *Efficient and fair scheduling of uplink and downlink in IEEE 802.16 OFDMA networks.* Proceedings of the IEEE Wireless Communications and Networking Conference, pp. 984-990, 2006.

[19] Y. C. Lai and Y. H. Chen, *A channel quality and QoS aware bandwidth allocation algorithm for IEEE 802.16 base stations.* Proceedingns fo the 22nd International Conference on Advanced Information Networking and Applications, pp. 472-479, 2008.

[20] Y. Cao and V. O. K. Li, *Scheduling algorithms in broadband wireless networks.* Proceedings of the IEEE, vol. 89, no. 1, pp. 76-87, 2001.

[21] 3GPP2 C.S0014-0, *Enhanced Variable Rate Codec (EVRC).*

Procedures

```
CheckDeadline:
for each request i at the intermediate queue do
  if availableBw = 0 then
    break
  if service[CID] = rtPS then
    frame[i] = ⌊(deadline[i] - currentTime)÷ frameDuration⌋;
    if frame[i] = 3 and TwndTR[CID] < minTR[CID] then
      MigrateBWRequest(i)

CheckMinimumBandwidth:
for each connection do
  efficiency[CID] = get physical efficiency of connection CID
for each connection of type rtPS or nrtPS do
  backlogged_tmp[CID] = backlogged[CID]
  TwndTR_tmp[CID] = TwndTR[CID]
  bucket2_tmp[CID] = bucket2[CID]
for each request i at the intermediate queue do
  if minTR[CID] ≤ TwndTR_tmp[CID] or bucket2_tmp[CID] = 0 then
    priority[i] = 0
  else
    priority[i] = (backlogged_tmp[CID] − ( TwndTR_tmp[CID] −
    minTR[CID])) * efficiency[CID];
    TwndTR_tmp[CID] = TwndTR_tmp[CID] + BR[i]
    bucket2_tmp[CID] = bucket2_tmp[CID] - BR[i]
    backlogged_tmp[CID] = backlogged_tmp[CID] − BR[i]
sort the intermediate queue
for each request i at the intermediate queue do
  if availableBw = 0 then
    break
  MigrateBWRequest(i)

DistributeFreeResources:
for each request i at the low priority queue do
  if availableBw = 0 then
    break
  MigrateBWRequest(i)

MigrateBWRequest(i):
if BR[i] > availableBw then
  grantSize = availableBw
else
  grantSize = BR[i]
if grantSize > bucket2[CID] then
  grantSize = bucket2[CID]
if 0 < grantSize < BR[i] then
  create a new request j for connection CID with BR[j] = BR[i] − grantSize
  insert request j in the end of the intermediate queue
BR[i] = grantSize
move request i to high priority queue
TwndTR[CID] = TwndTR[CID] + grantSize
bucket2[CID] = bucket2[CID] − grantSize
backlogged[CID] = backlogged[CID] − grantSize
availableBw = availableBw − grantSize
```

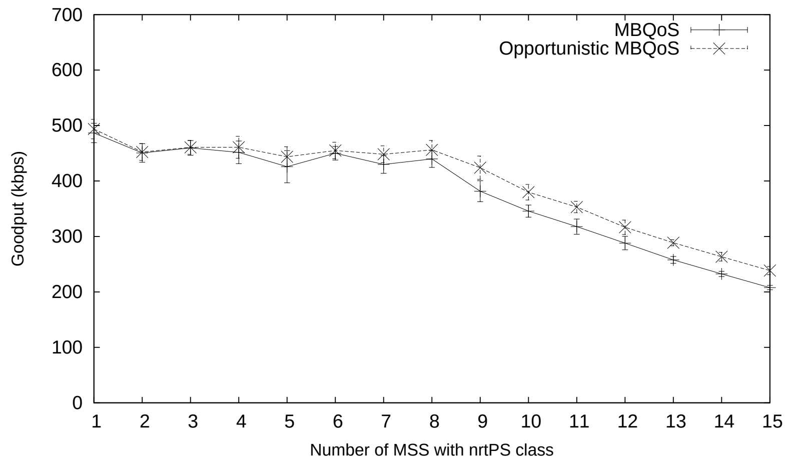

Figure 1: Mean goodput for nrtPS service flows

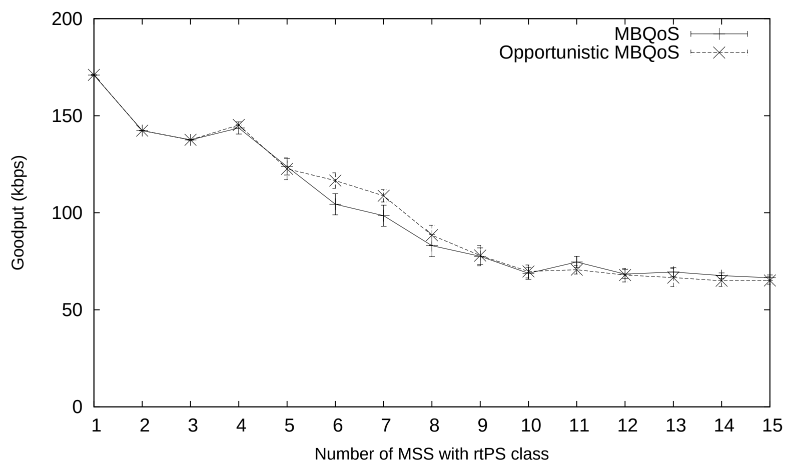

Figure 2: Mean goodput for rtPS service flows

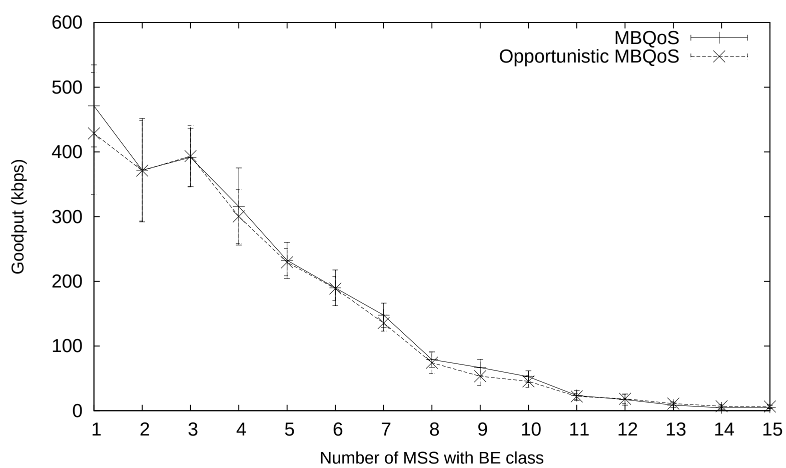

Figure 3: Mean goodput for BE service flows

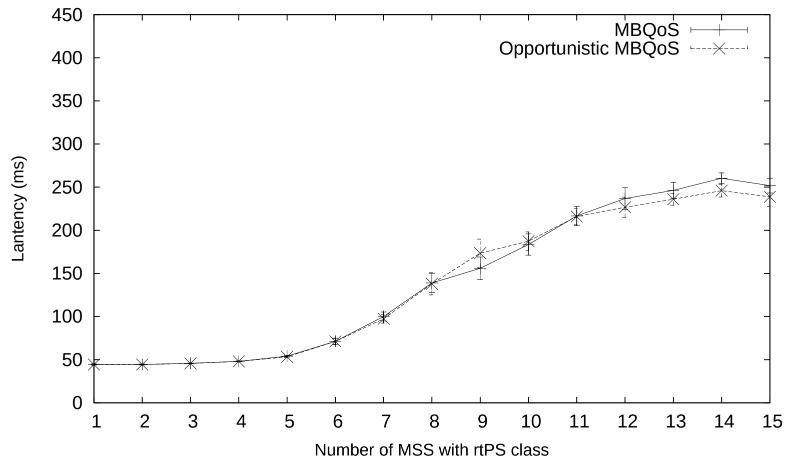

Figure 4: Mean latency for rtPS service flows

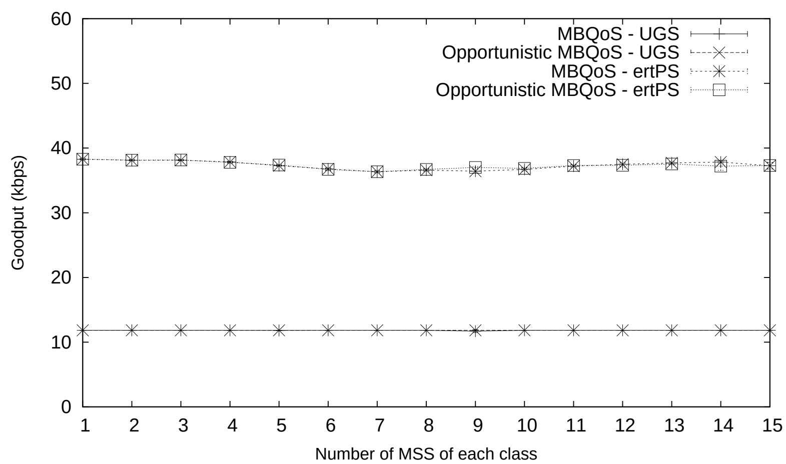

Figure 5: Mean goodput for UGS and ertPS services flows

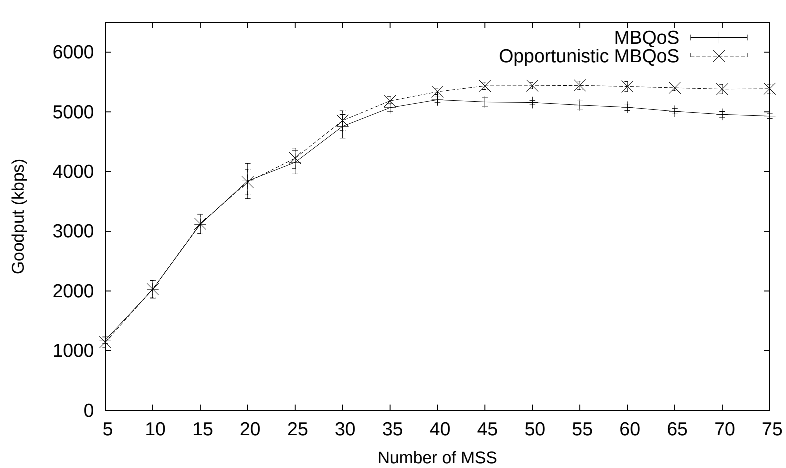

Figure 6: Mean goodput for all services flows