P-CAS: A Priority-Based Channel Assignment Scheme over Multi-Channel Cable Network for UGS Service Provisioning

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Abstract

Currently, the most popular standard adopted in cable network is the Data-Over-Cable Service Interface Specifications (DOCSIS) protocol. For supporting emerging multimedia applications, several QoS mechanisms and service types were defined in DOCSIS. DOCSIS, however, did not specify how to schedule these QoS-enabled traffics and thus this paper tries to offer a priority-based scheduling scheme with dynamic channel assignment to support the Unsolicited Grant Service (UGS). By considering the tolerated jitter and throughput of each request, we defined certain priority equations and channel assignment rules for the service scheduling. According to simulation results, our solution, named Priority-based Channel Assignment Scheme (P-CAS), provides decent service delivery rate, channel utilization ratio, channel load balance, and fair bandwidth utilization.

Key Words: Data-Over-Cable Service Interface Specifications (DOCSIS), Hybrid Fiber Coaxial (HFC), Cable Network, Quality of Service (QoS)

1. Introduction

With the improvements of computer and network technologies, Internet has almost become a necessity in our modern lives. It accelerates the growth of many modern applications, for instance, the Voice over IP (VoIP). For accessing these real-time multimedia applications, strict network quality is required for better experience.

To achieve this goal, cable network [1,2] is an solution. For customs, it provides sufficient bandwidth for more decent network experiences. For Internet Service Providers (ISP), the ability of supporting large amount of users as well as the fact that cable network is based on the widespread traditional analog cable network offer an easy installation environment, low investment costs, and a vast amount of potential customs.

Currently the most popular standard in cable network is the Multimedia Cable Network System's (MCNS) Data-Over-Cable Service Interface Specifications (DOCSIS). According to its definition, cable network is a central-controlled, multi-channel, and bandwidth-sharing network where all client users share the total network bandwidth. Although the whole network is administrated by Cable Modem Termination System (CMTS), the lack of bandwidth and scheduling schemes results that users who contend for transmission opportunities may not fairly share the resources. DOCSIS did define certain QoS [3,4] levels for different services, yet it did not specify how to schedule these QoS-enabled traffics due to the consideration that scheduling algorithms belong to implementation details and should be designed by each vendor to distinguish advantages of their products.

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Thus, this paper tries to figure out a scheduling scheme with dynamic channel assignment to support QoS for real-time applications which use the pre-defined Unsolicited Grant Service (UGS) in DOCSIS. The rest parts of this paper are organized as follows. Section 2 will introduce the cable network architecture. Section 3 gives an in-depth description of the most popular cable network protocol – the DOCSIS specification and the QoS provisioning. In Section 4, our proposed solution, basic concepts, and operations will be revealed. Simulation results are offered in Section 5 to see what we can benefit from the proposed scheme and finally the conclusion and future work are summarized in Section 6.

2. Cable Networks

Figure 1 is the physical architecture of a cable network. Headend is the main administrator and responsible for operations of the whole network. Cable Modems (CMs) connect users' PC to the Internet. Fiber nodes link the fibers and coaxial cables while the bi-directional amplifiers maintain the signal quality due to long-distance transmission in cable network. Below are some major features [5,6]:

- Tree and branch topology

  Cable network presents as a tree-topology, the headend serves as a root and spreads its links to subscribers by fiber nodes; and the whole network is wired with optical fibers and coaxial cables. Therefore, cable network is also called Hybrid Fiber Coaxial (HFC) network [7].

- Great amount of subscribers

  Cable network is consisted of several fiber nodes and theoretically each fiber node is capable of serving approximately 500 to maximum 2000 home subscribers [8] and all these connected subscribers share available resources within the same cable. Thus, there may be several thousands of users in a large scale cable network.

- Large propagation delay

  The maximum distance between the headend and the furthest CM could be a hundred miles away and thus the propagation delay is longer, usually reaching as 0.8 msec [1].

- Asymmetric upstream and downstream bandwidth

  In cable network, bandwidth is divided into upstream and downstream channels; CMs use upstream channels to transmit requests and data while headend uses downstream channels to send control messages and data to CMs. Because of the different frequency ranges in spectrum, cable network is an asymmetric bandwidth network. The total bandwidth of downstream channels (form the headend to CMs) are far more then that of the upstream channels (from CMs to the headend).

- Central-controlled network

  Cable network is a central-controlled network, where headend takes charge of all client users and each CM follows instructions of headend for data transmission. Headend assigns at least one Service ID (SID) to each CM and hence it can identify data packets according to SIDs.

3. MCNS DOCSIS Protocol

In DOCSIS, the CMTS coordinates all upstream/downstream channels and CMs. Figure 2 shows the minislot assignments in upstream/downstream channels of DOCSIS protocol. For transmission purpose, upstream/

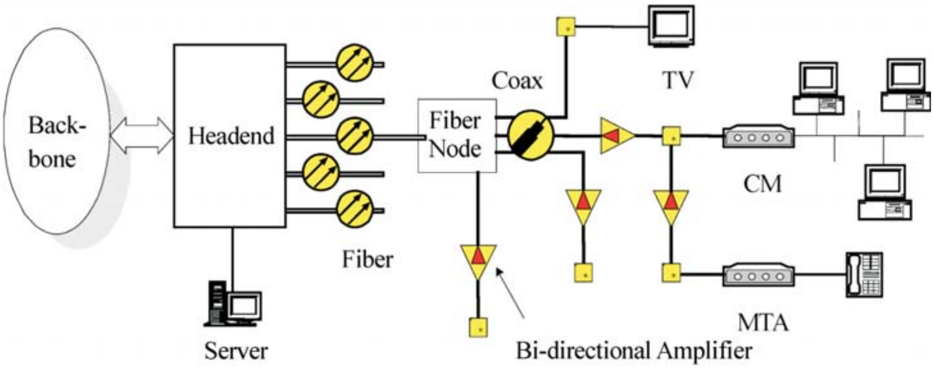

Figure 1. The cable network physical architecture.

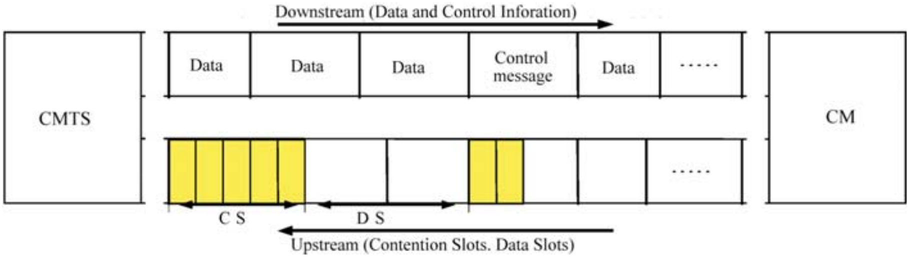

Figure 2. Minislots in up/downstream channels.

downstream channels in cable network are divided into many minislots of the same size. CMTS assigns minislots in the upstream channel as Contention Slot (CS) or Data Slot (DS). CMs use upstream channels to transmit requests and data within CS and DS while CMTS uses downstream channels to send control messages and data to CMs. By using the Bandwidth Allocation Map (MAP), CMTS notifies CMs the purpose of each minislot during a certain period in the upstream channel; and according to information in MAP, CMs transmit their requests or data packets within certain minislots.

3.1 Operation

Figure 3 illustrates the operation flow of the DOCSIS MAC protocol.

1. At time t_1, CMTS sends out MAP1. MAP1 describes the usage of each minislot in the upstream channel during t_3~t_8.
2. When MAP1 arrivals at t_2, CMs know the deployment of CSs in the upstream channel. If a CM wants to transmit data, it would use collision resolution scheme – Truncation Binary Exponential Backoff (TBEB) algorithm, to determine when to send out the request. Finally, the bandwidth request is sent at t_4.
3. CMTS receives the request at t_5, and then schedules all received requests. CMTS takes some admission control here and may schedule and assign service flows and minislots according to certain priority algorithm. When finish it sends out MAP2 at t_6.
4. CM gets MAP2 at t_7 and knows the deployment of minislots during t_8~t_{11}.
5. At t_9, CM knows its DSs which reserved by CMTS are coming and then transmits data within these DSs. Eventually, data Protocol Data Unit (PDU) reaches CMTS at t_{10}.

3.2 Quality of Service

For guaranteeing QoS to real-time applications, QoS mechanisms were added in DOCSIS. According to a set of QoS parameters such as latency, jitter, and throughput, traffics are classified into different service flows. Five service types, including UGS, UGS-AD, rtPS, nrtPS, and BE are supplied by DOCSIS protocol.

1. Unsolicited Grant Service (UGS): UGS is designed for supporting real-time services which require constant bandwidth such as the VoIP application. The CMTS must provide fixed size data grants at periodic intervals to the service flow.
2. Real-Time Polling Service (rtPS): rtPS is used for supporting real-time services which need variable amount of bandwidth periodically like MPEG vi-

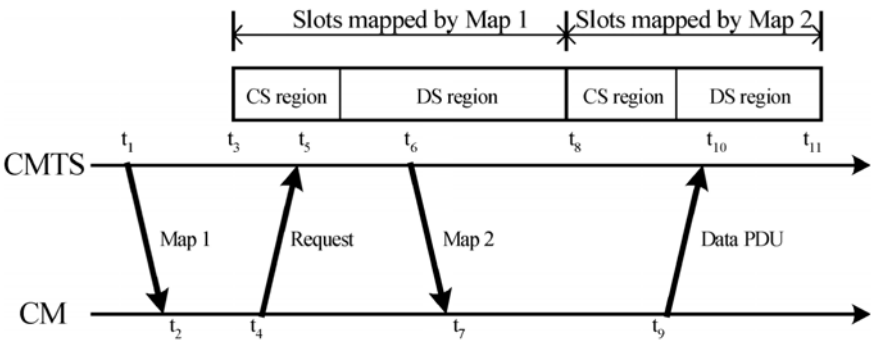

Figure 3. The DOCSIS MAC operation flow.

deo stream. For variable bit rate (VBR) traffics, the CMTS provides uni-cast request opportunities instead of data slots for this service type.

3. Unsolicited Grant Service with Activity Detection (UGS-AD): UGS-AD can support services like VoIP with silence suppression. When UGS-AD service flow is active, the CMTS reserves fixed amount bandwidth for them periodically. As the service flow is inactive, the CMTS offers uni-cast request opportunities alternatively. If an application wants to regain the UGS-AD service, it can do this through the request opportunities reserved by CMTS.
4. Non-Real-Time Polling Service (nrtPS): nrtPS is suitable for non real-time services like FTP. For flows which belong to this type, the CMTS provides uni-cast request opportunities during a certain period to avoid undelivered requests when network gets congested. nrtPS is similar to rtPS, yet has a longer polling interval around 1 sec or more.
5. Best Effort Service (BE): BE is the conventional service type. CM must send a bandwidth request through the CS to CMTS for contending transmission opportunities and thus no QoS is guaranteed.

Except for BE, other service types avoid request contentions by unsolicited grants or pollings. Unsolicited grants for collision-free data transmission which periodically issued by the CMTS allow CMs to transmit their data PDUs without bandwidth requests, while the polling service provides collision-free request opportunities so that packet access delay can also be guaranteed. Although DOCSIS clearly defined these five service classes for supporting QoS, it did not describe how to schedule these services. Thus, in this paper we try to propose a solution – Priority-based Channel Assignment Scheme (P-CAS) – for supporting real-time multimedia applications which use UGS or UGS-AD service.

3.3 Multi-Channel Operation

In the multiple downstreams and multiple upstreams architecture, the CMTS assigns individual MAP to each upstream channel and passes all MAPs to entire downstream channels. According to the Channel Identifier field in each MAP and the Upstream Channel Descriptor (UCD) messages assigned by CMTS, CMs in whole downstream channels can understand which MAP to access. The MAP access procedure of a CM is described as follows. First, since a downstream channel may have several MAPs, the CM randomly chooses an UCD message and then transmits a test signal through the upstream channel which described by the UCD. If test signal failed, another UCD would be chosen and the testing procedure be processed again. Second, after the successful testing, the CM scans the Upstream ID within each MAP and checks which one fit with its UCD. After finding out the corresponding MAP, the CM will use it for upstream channel transmissions.

4. The P-CAS

With the popularity of Internet, many real-time multimedia services are emerging. For enhancing the efficiency of supporting these time-critical traffics over cable networks, this paper proposed the P-CAS scheme. The P-CAS is consist of two phases; phase one for the prioritized service scheduling and phase two for the dynamic channel and minislot assignment. The P-CAS collects users' request info conveyed in CSs and gathers certain parameters such as jitter and throughput for scheduling priority for the next channel and minislot assignment process. It is functioned in the CMTS and CMs need not be touched. By using our scheme, we can provide more efficient bandwidth utilization rate and transmission opportunities for time-critical traffics like UGS services regardless of the channel load balance issue. Moreover, since DOCSIS is the most popular standard in cable network now, we follow the DOCSIS protocol to design the P-CAS in order to be compatible with the current cable devices.

4.1 Phase One – The Prioritized Service Scheduling Scheme

In the Step. 3 of Figure 3, as the CMTS finishes receiving requests from last Map circle, the phase one is triggered to schedule request priority. In phase one, we designed a prioritized scheduling scheme according to the maximum tolerated jitter and related CM throughput of a flow. Considering the system performance such as service blocking rate, throughput, and channel load balance, an appropriate scheduling scheme should be found out to maximize the performance.

Our proposed scheme aims for the provisioning of delay-sensitive flows like UGS services, thus we defined a parameter set <F_i, G_i, J_i, T_i, P_i> to present this kind of flows. These five parameters are defined as,

F_i: The packet inter-arrival time of a request,

G_i: The required grant size within each packet inter-arrival time,

J_i: The maximum variance of packet access delay a flow can tolerate,

T_i: The total throughput of a CM to which the request belongs,

P_i: The priority of a request.

F_i, G_i, J_i, and T_i are provided by a request when entering the system for scheduling, while P_i is given by the CMTS. For example, a service flow presents as <20, 1, 4, 133, 2.56> means that, the flow requires a data grant every 20 minislots, the maximum tolerated latency is 4 minislots, the total throughput of its CM is 133 minislots, and then from equation (1) below, the priority value calculated is 2.56.

4.1.1 Shortest Jitter First (SJF)

The primary priority equation is defined as,

$$\text{Priority } (P) = \frac{Ji}{\max(Ji, \forall Ji)} \times PJitter + \frac{Ti}{\max(Ti, \forall Ti)} \times PTroughput \qquad (1)$$

where J_i and T_i present as the tolerated jitter of a request and the total throughput of the related CM client, respectively. The max(J_i, ∀ J_i) indicate that we chose the maximum J_i value from those J_i group. *PJitter* and *PThroughput* are presented for evaluating how important the tolerated jitter and throughput factors may affect the system. In simulations we will give different *PJitter*/*PThroughput* values to show how the system performs. In addition, the lower the *P* value, the higher precedence a request will enter the system.

4.1.2 Largest Jitter First (LJF)

The secondary equation is given as,

$$\text{Priority } (P) = \frac{Ji}{\max(Ji, \forall Ji)} \times \frac{1}{PJitter} + \frac{Ti}{\max(Ti, \forall Ti)} \times PTroughput \qquad (2)$$

which made as a contrast to see what may happen if a request with higher tolerated jitter enters the system first.

4.2 Phase Two – The Dynamic Channel and Minislot Assignment Scheme

After prioritizing requests in phase one, the next phase is to assign channel and minislots. Since the P-CAS is based on the multiple downstreams and multiple upstreams architecture, we describe the advantages and concepts of our phase two operation.

The original MAP operation, however, will cause certain issues,

- As a CM finds out an available upstream channel through the UCD message, it would only access the corresponding MAP and ignore other MAPs. This may reduce the channel utilization efficiency as well as the channel load balance.
- For CMs, they are forced to receive many useless MAPs in downstream channels and this may lead to bandwidth and processing time overheads.

Thus, we take some changes to the original MAP access method. In our dynamic channel and minislot assignment scheme, the CM uses all MAPs but not only the one which described by the single pre-assigned UCD. The CM receives entire MAPs' info, and then decides in which period to use which upstream channel for data transmission. To sum up, we give the enhanced multi-channel access method below,

- CMTS allows a CM to be described by several UCD messages, thus CMs can use multiple upstream channels to transmit data.
- Minislots in all MAPs are synchronized, and hence transmissions of entire upstream channels can be synchronized too.

Since CMs can use multiple upstream channels, a channel and minislot assignment policy should be defined and certain restrictions such as channel switching delay and channel load balance need to be considered. Below are some considerations:

1. Channel Load Balance Issue

Due to the unbalanced nature of the CM utilization rate in each upstream channel and the consequence resulted from the changeable channel assignment, the loading in each upstream channel may be unequal and lead to performance drop, for instance, the increased service blocking rate. Hence, we defined the Fair Channel Assignment (FCA) scheme here. It fairly assigns each service flow into different upstream channels according to loadings in that moment. In other words, a channel with lowest loading will be chosen first to allocate flows. It's simple and nearly takes no computational time.

2. Channel Switching Delay

For each channel switching operation, a delay time is required. When a channel switching is taken at time t_i, the delay time restriction should be examined first. If we assume the switching delay is δ minislots, then slots within the ranges $t_i + \delta$ in other channels are forbidden to be assigned to a flow.

Figure 4 shows the P-CAS flow diagram. As the CMTS finishes receiving bandwidth requests, it will then calculate the priority value for each flow according to their requirements and some statistics. After sorting the flow precedence, then a simple admission control will be taken to examine if the required bandwidth exceeds what the system can offer. If a flow is to be checked applicable, then scheduling procedure starts. First the P-CAS picks up the idlest channel, and then verifies that whether all the required data grants can be stuffed into a single channel. If not, it will search other channels for available slots to replace the occupied ones in the original channel. If there are still no valid slots can be borrowed, the request will be denied. When whole requests are processed, a new MAP will be generated and send out to CMs.

5. Simulation and Evaluation

We built a simulation program to evaluate our scheme. Common simulation parameters are listed in Table 1. Considering the emerging of voice/video applications over IP networks, we take the voice/video compression protocols, ex. G.711 and H.261, as our emulated traffic types. The duration of one minislot is viewed as the elementary time unit and all simulation results are measured based on it. In this simulation, we will make a discussion on the priority calculation policy includes the weights of the *PJitter* and *PThroughout* factor, which define how the priority calculation should be done depends on the tolerated jitter and total throughput of each CM client, will be given.

We will demonstrate the simulation results with the phase one and phase two schemes in aspects of the UGS service blocking rate, throughput, channel load balance ratio, and fairness of bandwidth utilization and finally reveal the best phase one + phase two combination.

Below are these definitions. UGS service blocking rate means the reject ratio of bandwidth requests; the lower the value, the higher the possibility of successful transmissions. Throughput is the ratio of gained and required bandwidth. The throughput efficiency would be better if the value approaching 1. Channel Load Balance reflects the traffic of each channel and the value of 1 means that each channel has the same traffic loading and is ideal for our P-CAS. Finally, Bandwidth Usage Fairness indicates whether all clients fairly share the total network bandwidth and the value of 1 is the best.

$$\text{UGS Service Blocking Rate} = \frac{\sum_{i=0}^{n} \text{Denied requests of a map } Di}{\sum_{i=0}^{n} \text{Total requests of a map } Ri}$$

$$\text{Throughput} = \frac{\text{Actually gained bandwidth in whole simulation time}}{\text{Total required bandwidth whole simulation time}}$$

$$\text{Channel Load Balance} = \frac{\text{Traffic loading of Upstream Channel \#1}}{\text{Traffic loading of Upstream Channel \#2}}$$

$$\text{Bandwidth Usage Fairness } (F) = \frac{(\sum xi)^2}{n\sum xi^2},$$

where xi is the ratio of the actual throughput to the fair throughput for source i.

5.1 Exp. 1: The Pjitter (PJ) and Pthroughput (PT) Factors Based on SJF

In this experiment, we emphasize on the phase one prioritized service scheduling scheme. Here we use the SJF mentioned in Section 4 and take certain experiments on giving different weights, including 0.25/0.75, 0.5/0.5, 0.75/0.25, 1/0, and 0/1, to *PJitter (PJ)* and *PThroughput (PT)* to dig out the best configuration of these two parameters. We choose the FCA for the phase two channel

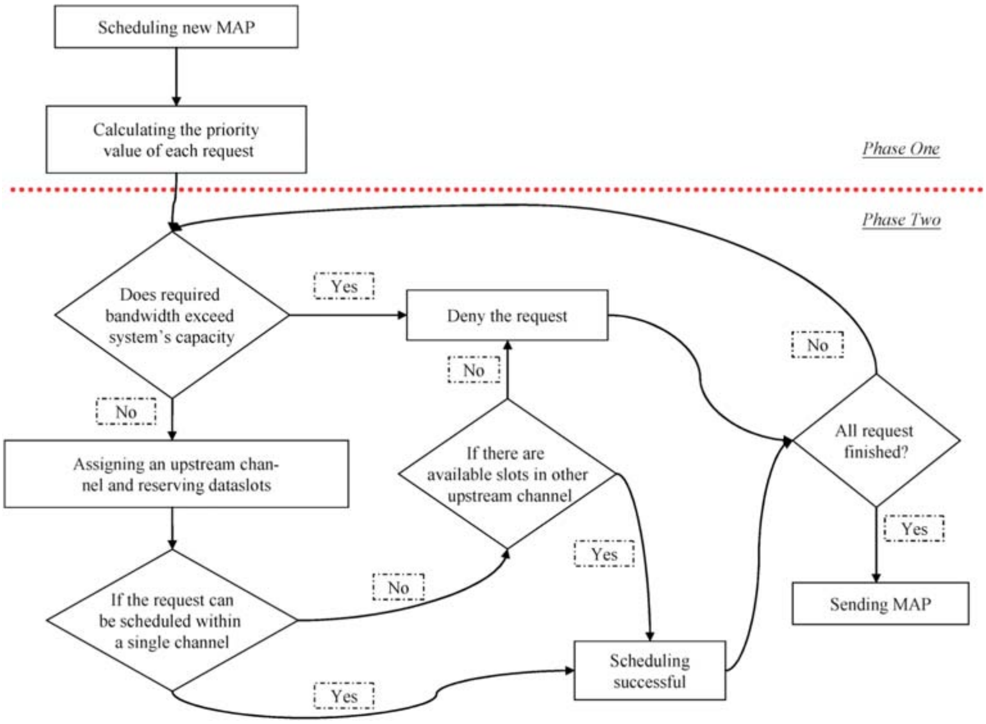

Figure 4. The P-CAS flow diagram.

Table 1. Simulation environment

Parameter	Value
Number of CMs	500
Number of upstream channels	2
Number of downstream channels	1
Single upstream channel capacity	5.12 Mbits/sec
Minislot duration	25 micro second
Minislot size	16bytes
Simulation Time	4,800,000 minslots
Maximum length of UGS flow	400,000 minslots
Minislots/second	40,000

Traffic type	Bit Rate	Tolerated Jitter (minislot)
UGS#1 (Broadcast)	51.2 kbps	10
UGS#2 (G.723.1)	20.48 kbps	25
UGS#3 (G.711)	64 kbps	8
UGS#4 (H261)	128 kbps	4
UGS#5 (H.263)	25.6 kbps	20

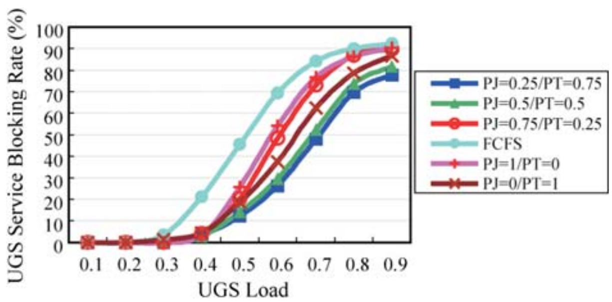

Figure 5. The UGS service blocking rate comparison on different *PJ*/*PT* weights with SJF.

and minislot assignment process.

The UGS service blocking rate of SJF with different *PJ*/*PT* weights is presented in Figure 5. First of all, by comparing the 1/0 and 0/1 setups, we can clearly understand that the throughput factor significantly impacts the service blocking rate than the tolerated jitter factor. While we further compare the 0.25/0.75, 0.5/0.5, and 0.75/0.25 combinations, the true are told again and the 0.25/0.75 setup wins the race. An interesting matter is observed that the curve of 0.75/0.25 is between those of the 1/0 and 0/1, more precisely, it is much closer to the 1/0 curve and above the 0/1 one; this also indicates the greater importance of *PT* factor. The FCFS scheme is shown here for a contrast and it also performs worst.

Figure 6 shows the throughput of each *PJ*/*PT* setups. Whole *PJ*/*PT* setups offer sweet results except for the FCFS scheme, where the difference is recognized from 0.5 UGS load. When UGS load is 0.9, our scheme with *PJ*/*PT* values set to 0.25/0.75 can supply nearly 80% throughput while the FCFS can only reach 55%.

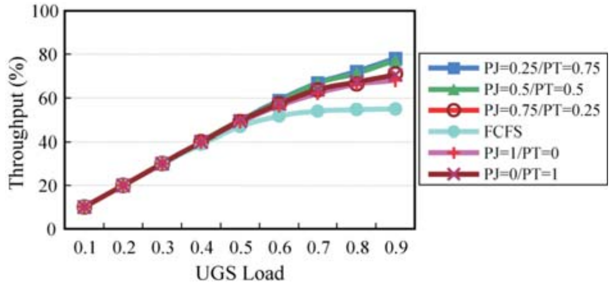

Figure 6. The throughput comparison on different *PJ*/*PT* weights with SJF.

Figure 7 is the channel load balance comparison. All setups do great jobs here and this benefit should thank to the FCA of phase two.

Finally, the bandwidth usage fairness is shown in Figure 8. Except for the FCFS scheme, all other setups perform well; and as we observe, the 0.25/0.75 combination gives an excellent outcome which provides fairest bandwidth utilization rate at all UGS loads. Thus we have a conclusion that the *PThroughput* factor gives greater impact on the phase one performance than *PJitter* does.

5.2 Exp. 2: Another Interesting LJF Priority Equation

To be a contrast, and for interesting, another priority calculation equation differed from SJF is also given. In contrast to SJF, LJF is made intentionally to observe what may happen if a request with higher tolerated jitter enter the system first and also verify that whether the 0.25/0.75 PJ/PT setup would still dominate. The *PJ*/*PT* setups are just like those given in Exp.1 and the FCA of phase two is chosen again.

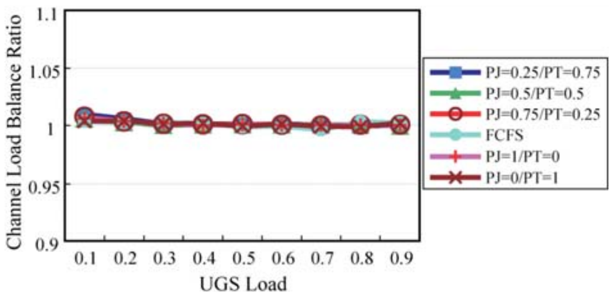

Figure 7. The channel load balance comparison on different *PJ*/*PT* weights with SJF.

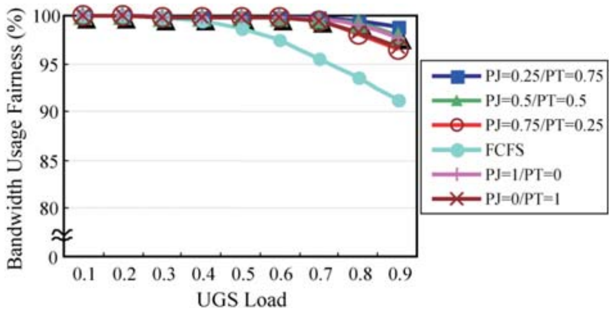

Figure 8. The bandwidth usage fairness comparison on different *PJ*/*PT* weights with SJF.

From Figure 9, except for the 0/1 and FCFS setups, all other *PJ*/*PT* setups get bad performance on UGS service blocking rate, especially the 1/0 one; which means the earlier a request with larger tolerated jitter enter the system, the higher the possibility it will block other urgent requests. Among all these *PJ*/*PT* setups except 0/1 and FCFS, the 0.25/0.75 combination outperforms others although it can only compete with FCFS.

Figure 10 and 12 reveal the throughput and bandwidth usage fairness performance, respectively. Again, exclusive of the 0/1 and FCFS setups, the 0.25/0.75 combination still dominates over others. Figure 11 is the channel load balance comparison. Here all setups are almost equal with each other and do well due to the adoption of FCA in phase two.

For summary of Exp.2, we conclude that the 0.25/

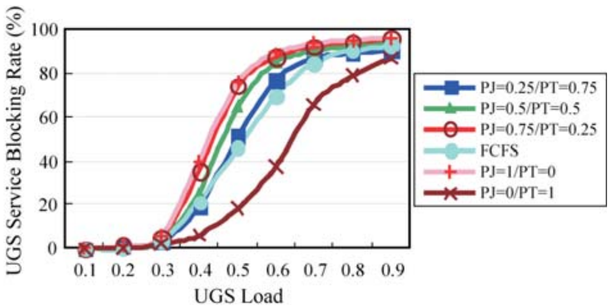

Figure 9. The UGS service blocking rate comparison on different *PJ*/*PT* weights with LJF.

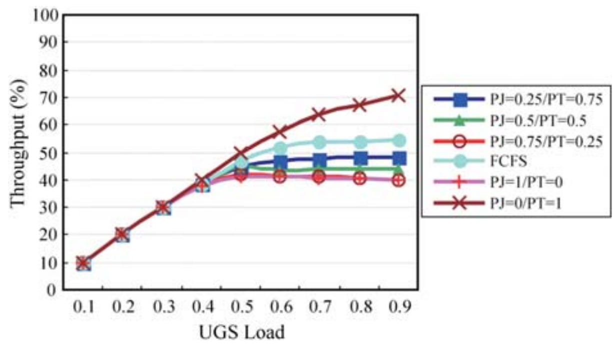

Figure 10. The throughput comparison on different *PJ*/*PT* weights with LJF.

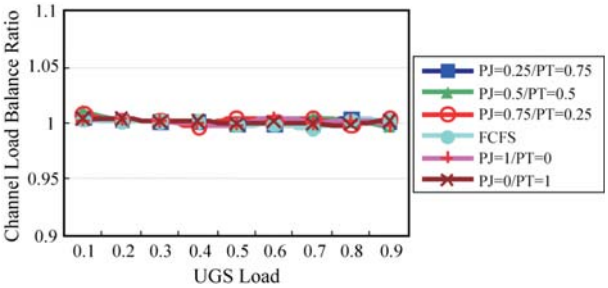

Figure 11. The channel load balance comparison on different *PJ*/*PT* weights with LJF.

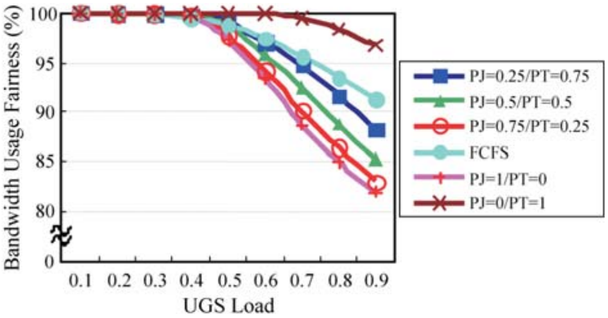

Figure 12. The bandwidth usage fairness comparison on different *PJ*/*PT* weights with LJF.

0.75 combination is still the best choice among the 0.75/0.25, 0.5/0.5, and 1/0 setups even we consider requests with larger jitter enter the system first.

5.3 Exp. 3: The Best Phase One + Phase Two Scheme

Be the final part of this section, we give certain results on all phase one + phase two schemes and demonstrate the best one. Figure 13, 14, 15, and 16 show the results. From these results and discussions of Exp.1 and 2, we conclude that the SJF priority equation with the FCA scheme is the most suitable combination for phase one and phase two processes.

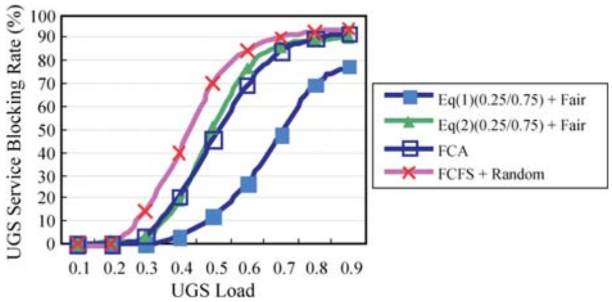

Figure 13. The UGS service blocking rate comparison on phase one + phase two scheme.

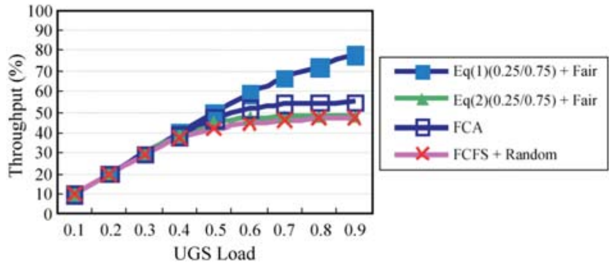

Figure 14. The throughput comparison on phase one + phase two scheme.

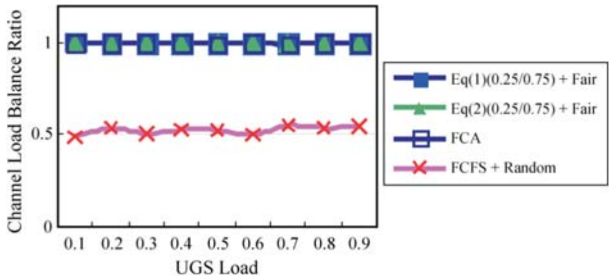

Figure 15. The channel load balance comparison on phase one + phase two scheme.

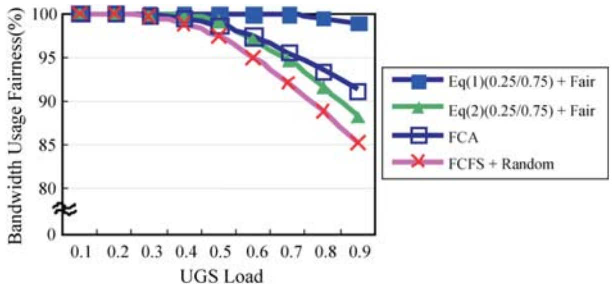

Figure 16. The bandwidth usage fairness comparison on phase one + phase two scheme.

6. Conclusion

Cable network is a considerable alternative for the modern multimedia applications. It supports great amount of client users as well as sufficient bandwidth and hence becomes a decent solution for those multimedia services. However, although cable network is a centralized network and all data transmissions must be granted by CMTS, the innate characteristic – bandwidth sharing – causes some issues. For example, because users in cable network share the total upstream bandwidth, the more the users the less the bandwidth shared by each other. Also, the lack of bandwidth and channel management scheme results that users may not fairly use the bandwidth even though they all pay the same rents; and the channel load-balance issue usually occurs.

Hence, this paper proposes a prioritized scheduling scheme with dynamic channel assignment to fairly manage network bandwidth, channel load balance, and provide UGS services while keeping the blocking rate and throughput at a reasonable scale. Form the simulation results given in Section 5, besides fairly allocate bandwidth, our mechanism can efficiently improve the total network throughput as well as the channel load balance, and keep the UGS service blocking rate in low. Exp.1 shows that the SJF with $PJ = 0.25/PT = 0.75$ has the best performance in the four testing items. Exp.2 also denotes the PJ/PT with values 0.25/0.75 is the ideal setting for our P-CAS phase one priority calculation even with regard to the LJF equation. Finally the Exp.3 unfolds the best phase one and two algorithms for P-CAS are the SJF with $PJ = 0.25/PT = 0.75$ and the FCA.

With the increasing amount of Internet users and new type multimedia services, such a scheduling and assignment scheme of the precious network resources would be a critical subject in the future.

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