An Adaptive Fast Expansion, Loading Statistics with Dynamic Swapping Algorithm to Support Real Time Services over CATV Networks

Chih-Cheng Lo, Hung-Chang Lai, and Wen-Shyen E. Chen

Abstract: **As the community antenna television (CATV) networks becomes ubiquitous, instead of constructing an entirely new broadband network infrastructure, it has emerged as one of the rapid and economic technologies to interconnecting heterogeneous network to provide broadband access to subscribers. How to support ubiquitous real-time multimedia applications, especially in a heavy traffic environment, becomes a critical issue in modern CATV networks. In this paper, we propose a time guaranteed and efficient upstream minislots allocation algorithm for supporting quality-of-service (QoS) traffic over data over cable service interface specification (DOCSIS) CATV networks to fulfill the needs of real-time interactive services, such as video telephony, video on demand (VOD), distance learning, and so on. The proposed adaptive fast expansion algorithm and the loading statistics with dynamic swapping algorithm have been shown to perform better than that of the multimedia cable network system (MCNS) DOCSIS.**

Index Terms: **Cable modem, collision avoidance, community antenna television (CATV) networks, contention resolution, data over cable service interface specification (DOCSIS), hybrid fiber coaxial (HFC).**

I. INTRODUCTION

We have witnessed the development of many network technologies being developed to deliver multimedia and broadband services over communication networks. Several emerging wireline and wireless access network technologies to provide broadband access to the subscribers, such as community antenna television (CATV) networks, digital subscriber line (DSL), fiber to the x (FTTx), unversal mobile telecommunication system/code division multiple access (UMTS/CDMA), and local multipoint distribution system/multichannel multipoint distribution service (LMDS/MMDS) access networks [1], had been deployed. Among them, CATV networks have emerged as one of the major and economic technologies to converge heterogeneous network to provide broadband access to subscribers [2]–[6]. We have also seen the following three facts about the CATV networks: First, the ubiquitous deployment and high acceptance rate of CATV networks. Second, it requires reasonable cost to upgrade the existing cable plants into high-speed, two-way hybrid fiber coaxial (HFC) networks. Third, CATV networks have rather wide bandwidth to provide broadband services. Due to the nature of truncated binary exponential back-off algorithm used by data over cable service interface specification (DOCSIS) CATV networks, the maximum access delay to support real-time applications, especially in a heavy traffic environment, could not be guaranteed. In this paper, we propose an adaptive fast expansion, loading statistics with dynamic swapping algorithm to support quality of service (QoS) in CATV Networks to fulfill the real-time applications over DOCSIS CATV networks.

There are many organizations recommending the media access control (MAC) layer protocols as the standard of modern CATV networks to be an open standard for CATV network systems [7]. The major standards activities working on this field include the multimedia cable network system (MCNS) Partners Ltd. [8], the IEEE working group 802.14 [9], the Internet engineering task force (IETF) IP over cable data network working group [10], the ATM forum residential broadband working group [11], the European cable communication association (ECCA) [12], the digital audio video council (DAVIC) [13], the digital video broadcasting (DVB) [14], society of cable telecommunications engineers (SCTE) [15], [16], and ITU. Both DOCSIS and IEEE 802.14a were developed to facilitate the interoperability between stations and headend (HE) designed by different vendors. Due to the delayed progress, the IEEE 802.14 working group was disbanded in March 2000, while MCNS DOCSIS was approved as a standard by the ITU and currently has the market dominance [7]. The CATV networks employ a shared-media, tree-and-branch architecture with analog transmission. Modern cable networks use both coax and fiber optic cables for transmission of media and are referred to as hybrid fiber/coax (HFC) networks. Fig. 1 illustrates the architecture of HFC networks. The bandwidth is divided into several channels, since CATV networks are originally developed for program broadcasting, most of the usages are for downstream transmission (from the HE to the stations), while upstream transmission (from the stations to the HE) accounts for only a small fraction of the usage. Cable modems in the customer premise cannot monitor collisions because their receivers and transmitters are tuned to different frequencies for the downstream and upstream channels. As more than one station can transmit a short request message at the same time, a contention resolution algorithm must be implemented as part of the MAC protocol. We can summarize that the HFC network has the following features that influence its operations [17]:

- Tree-and-branch topology and centralized control,
- asymmetric upstream and downstream operation and bandwidth,
- metropolitan area networks (MAN) topology,
- shared medium with broadcasting,
- non-uniform traffic burst and distribution.

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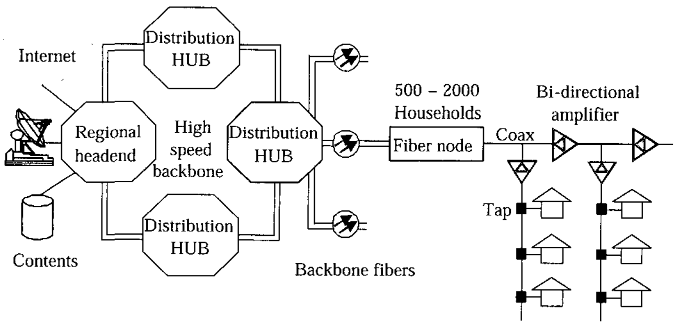


Fig. 1. The architecture of HFC networks.

With the abovementioned architecture and characteristics, the support of QoS requirement on CATV networks, especially in real-time interactive services, such as video telephony, video on demand, and distance learning, has been a challenging issue. To resolve this issue, Sala, Limb, and Khaunte [18] presented a contention slot allocator (CSA) at the HE to dynamically distribute the overall channel bandwidth between the contention channel and reservation channel. However, it does not support priority access. Furthermore, Kuo *et al.* [19] presented a multilevel priority collision resolution scheme with adaptive contention window adjustment; Hawa and Petr [20] described an efficient scheduling architecture to support bandwidth and delay QoS guarantees for both DOCSIS and IEEE 802.16. Their work still uses binary exponential back-off algorithm to treat different requirements' requests and does not guarantee the maximum access delay. Corner *et al.* [21] proposed a multilevel priority based collision resolution scheme to achieve the capability for preemptive priorities. The authors in [22] and [23] also proposed some strategies to support QoS guarantees over CATV networks.

As access delay and QoS are the key issues of broadband networks, the objective of this paper is to find an effective algorithm to improve the DOCSIS CATV networks and to support the real time services over CATV networks. The remainder of this paper is organized as follows. Section II presents the overview of HFC networks, including the MAC layer operation, collision resolution protocol (CRP) and QoS. In Section III, an adaptive fast expansion algorithm with coordinate centralized control is constructed and studied. For improvement performance moreover, a loading statistics with collision avoidance algorithm is devised in Section IV. The simulation results and discussion was shown in Section V. Finally, we make a brief conclusion in Section VI.

II. OVERVIEW OF HFC NETWORKS MAC LAYER OPERATIONS

The architecture of CATV networks is based on shared-medium, tree-and-branch topology as shown in Fig. 1. The bandwidth allocations are separated into upstream and downstream paths. The downstream path ranges from 50 MHz to 860 MHz and adopts FDMA to slice each channel into a 6 MHz bandwidth selected by the cable operator. Frequencies ranging from 5 MHz to 54 MHz are used for upstream channel and adopt FDMA combined with TDMA mechanism to slice each channel into smaller bandwidth units. Since the downstream and upstream occupy the different bandwidth segements, the stations cannot listen to the upstream channels, and therefore unable to detect collision by themselves. Consequently, the operation of bandwidth allocation, contention resolution, and traffic scheduling are centrally controlled at the HE.

Upon initialization, the station can learn the characteristics of the upstream channel from the specific management messages broadcast by the HE. At startup, each CM MAC determines its upstream timing adjustment value through a procedure known as "ranging." The objective of ranging is to accurately measure the time offset from the HE to a specific station. Therefore, the synchronization between the HE and the station could be achieved by tuning the station's time according to the measured value.

The upstream channel is modeled as a stream of minislots. There are two types of minislots: Contention slots and data slots; both of them are apportioned by the HE. Contention slots are used to convey bandwidth requests created by stations before transmission of data; while data slots are used by stations for sending data after their requests had been granted by the HE. The DOCSIS MAC protocol uses a request/grant mechanism to communicate between the HE and stations. The HE periodically broadcasts a bandwidth allocation map (MAP) in the downstream channel, which contains the upstream bandwidth allocation information, to notify all stations the upstream channel allotment and the usage of minislots. Stations learn the assignments from the MAP and operation accordingly. In case of any collision, a collision resolution protocol (CRP) is invoked in order to resolve collisions resulting from two or more stations requesting contention minislot simultaneously. Many studies on contention resolution algorithms can be seen in [24]–[27]. To reduce implementation complexity and cost, DOCSIS adopts *truncated binary exponential back-off algorithm* to resolve collisions in the request minislot contention process.

The HE controls the initial access to the contention slot by setting data back-off start (DBS) and date back-off end (DBE) specified as part of the MAP MAC message. When a station has data to send, it sets its internal back-off windows according to the data back-off range indicated in the allocation MAP. Since the station cannot detect whether there is a collision or not, it should wait for the HE to send back either a data grant or an acknowledgement (Ack) in the subsequent allocation MAP. If the station does not receive either data grant or Ack in the subsequent allocation MAP, it indicates that a collision occurred. In this case, the station must then increase its back-off windows by a factor of two as long as it is less than the data back-off end value set in the allocation MAP. Once again, the station randomly selects a number within its new window range and repeats the contention process depicted above.

To support various applications of CATV networks, DOCSIS 1.1 and above offers QoS by classifying packets into a service flow based on its QoS requirements. A service flow is a MAC-layer transport service that provides a particular QoS and unidirectional transport of packets either to upstream packets transmitted by the station or to downstream packets transmitted by the HE. The upstream service flow scheduling services are classified into six classes as follows:

- Unsolicited grant service (UGS),
- unsolicited grant service with activity detection (UGS-AD),

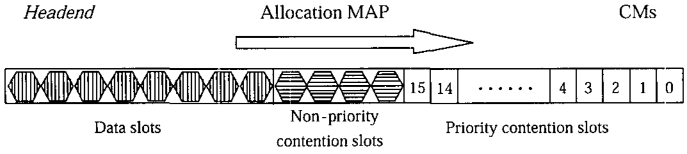
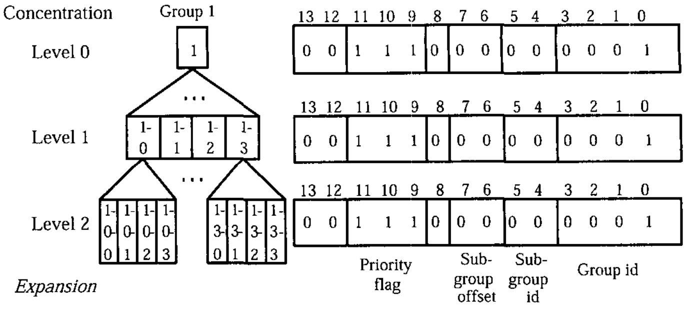


Fig. 2. Assignment of proposed upstream minislots.



For example: Priority-SID = 00,1110,0000,0001

Fig. 3. Structure of group hierarchies and the priority-SIDs.

- real-time polling service (rtPS),
- non-real-time polling service (nrtPS),
- best effort (BE) service,
- committed information rate (CIR) service.

To meet the QoS requirements, the HE must adopt an admission control mechanism and a scheduling algorithm among different services to reduce the QoS violation probability. Normally, each QoS flow matches exactly one QoS service. If a station has a special bandwidth requirement not specified in the QoS service profile, it could dynamically request a service by sending a dynamic service addition request (DSA-REQ) message to the HE. Moreover, after a QoS flow is established, the payload header suppression mechanism can be adopted to efficiently utilize the bandwidth by replacing the repetitive portion of payload headers with a payload header index.

III. AN ADAPTIVE FAST EXPANSION ALGORITHM WITH COORDINATE CENTRALIZE CONTROL

A. Motivation and Problem Description

Although DOCSIS provides six QoS service classes to distinguish service flows, but when a station wants to send its requests, it should follow the *truncated binary exponential back-off algorithm* to access contention minislots. The back-off may repeat unpredictable number of times because of the random selection from one of the back-off windows and therefore cannot guarantee the maximum access delay to support real-time applications, especially in highly traffic environment.

To avoid the inherent unpredictable access delay of the truncated binary exponential back-off algorithm, we propose a new expansion scheme and collision avoidance method for priority traffic over DOCSIS CATV networks to support real-time interactive services. It consists of two algorithms: An adaptive fast expansion algorithm with coordinate centralized control, and a loading statistics with dynamic swapping algorithm. We will introduce the former algorithm in this section and the latter in the next section.

B. Adaptive Fast Expansion Algorithm

In DOCSIS HFC networks, a fiber node is designed to support about 2000 households. Assume that there are at most around 12.5%, i.e., 256 households, that will register for real-time services at the same time. Therefore, in this paper, we adopt 256 priority stations to design the subscriber traffic model. This model can be easily extended to work with more priority stations, and we have reserved its address allocation in proposed method.

We divide the upstream contention slots into two regions: Priority and non-priority contention slots, as shown in Fig. 2. If it is a non-priority request flow, then the flow still follow DOCSIS to contend the contention slot and does not discuss in this paper. Otherwise, it belongs to priority request flow and will invoke the proposed algorithm to contend the priority contention slot. In our scheme, every priority flow will be assigned a priority service-identification (priority-SID) as shown in Fig. 3. Each time when a station wants to request a priority service, it should first register to the HE, and then will receive a priority-SID to identify this priority flow. The registration can be held in the initial phase or any time later when the station invokes a priority service. To simplify the simulation model, suppose each CM has only one priority service flow each time. DOCSIS defines the service ID to be a 14-bit code assigned by the HE to identify each service flow. We have modified the format of DOCSIS service ID slightly and add some definition to meet our system requirements, as described in the following.

First, fast identifying and spreading priority-SID: In DOCSIS, unicast Service IDs are defined from 0x0001 to 0x1FFF. The format of proposed priority-SID is based on DOCSIS and also a 14-bit identification as shown in Fig. 3, where bits 0 to 3 stand for level 0 group-id, bits 4 to 5 stand for level 1 subgroup id, and bits 6 to 7 stand for level 2 sub-group offset. Moreover, bit 8 is reserved for address extension, and bits 9 to 11 are priority flags, where 111 represents the highest priority, and 000 stands for a non-priority request flow. We also reserve other priority levels from 001 to 110 to represent different priority levels for future study. The idea of a group intends to allow many priority stations to share one priority contention slot to save the usage of slots because upstream bandwidth is scarce and stations do not always have priority requests to send at all times. The proposed fast identifying and spreading group method is to quickly assign the group id, sub-group id and sub-group offset of each priority-SID in a sequence paradigm and to spread continuous priority-SID into different groups. The design of level 0 group identifying has an inverse sequence from the least significant bit (LSB), instead of the most significant bit (MSB), i.e., bits 0 to 3 stand for level 0 group-id. This design has innate distribution character because those sequential SID will be allotted to different group ids that causes the sequence SID to be scrambled in different level 0 groups and decreases collision probability because of locality property of stations. Therefore, sequential id will distribute at different groups. For example, continuous priority-SID 00,1110,0000,0001 and 00,1110,0000,0010 will be allotted in groups 1 and 2, respectively. Moreover, priority-SID

00,1110,0000,0010 and 00,1110,0001,0010 will share the same priority contention slot at level 0, but a different priority contention slot at level 1.

Second, construct group hierarchies: The proposed hierarchy model is shown in Fig. 3, where the priority-SIDs are divided into three levels in hierarchical architecture, from level 0 to level 2. For each level 0 group consists of four level 1 sub-groups. Again, for each level 1 sub-group consists of four level 2 sub-group offsets in a similar manner. Those priority contention slots are in front of non-priority contention slots of the upstream minislots, as shown in Fig. 2. The HE notifies all stations about those grouping information through the MAP. Each level 0 priority contention slot supports up to sixteen priority stations to share one contention slot, while each level 1 priority contention slot supports four priority stations to share one priority contention slot. Finally, each level 2 priority contention slot just supports one priority station exactly and no collision occurs. This is to save the resource of priority contention slots since upstream resource is scarce in CATV networks.

Third, adaptive fast expansion and concentration: To accelerate expansion and concentration speed to reduce contention resolution time, we propose an *adaptive fast expansion and concentration algorithm* as shown in Table 1. In the default operation mode, i.e., normal expansion mode, when some groups of level 0 collisions happen, those contention groups will expand to level 1 and spread into four slots, each has a level 1 subgroup id extended from level 0 and the HE will notify stations through the subsequent MAP. Those collision group stations interpret this collision and will automatically expand to level 1 by the fast adaptive expansion algorithm and then send their requests during the relative priority contention slots in the subsequent MAP. If it is a successful request, then HE will send an acknowledgement via the subsequent MAP to notify those stations. Otherwise, it means collision happened again, all relative stations understand and will automatically expand to level 2 and prepare to send their requests again. The HE will also expand to level 2 for those collided sub-groups and notify those stations to send its request again via the MAP. No collision will happen this time, because in level 2, every station has exactly one priority contention slot to serve it. In other words, the maximum cycle of collision resolution is under three rounds and could guarantee the maximum access delay to be control in an acceptable value.

Table 1. Algorithm 1.

```
//Identifying and spreading phase
For each new comer {
  Quickly assigning a priority-SID and automatic spreading
  Construct the level 0 to level 2 group hierarchies
}
//Statistics phase
Statistics all group level 0 and level 1 collision numbers in
    past twelve cycles; (More details are given in Algorithm 2)
//Expansion phase
For each $Group_i$, $i = 0$ to $k - 1, k = 16$ {
  If $Group_i$ collisions amount is greater
than $C(t)_H$
     Quick expansion mode and go directly to level 2
  Else
     Normal expansion mode and expand to next level
}
The HE sends MAP to CMs
//Transmission phase
  CM request successfully
  CM waits for upstream transmission
  Upstream transmission
//Concentration phase
If all slots of the same level are idle
  If $Group_i$ collisions amount is less
than $\overline{C}(t)$
     Quick concentration mode and go directly to level 0
  Else
     Normal concentration mode
  Else
     Remaining at current level
Restart the next cycle
```

To accelerate expansion and concentration speed of the MAP, we introduce two different modes in this algorithm: Normal expansion/concentration mode and quick expansion/concentration mode. In normal mode, the default mode, it expands/concentrates one level each time when a collision occurs. For example, when it originates in level 0 and a collision occurs, it will expand from level 0 to level 1. Instead of normal mode, the quick mode may directly expand/concentrate two levels to accelerate operation speed in heavy collision situations and to save the access delay caused by intensive contentions. With the statistics of the collision number, if the collisions amount of some groups are greater than the high threshold, $\bar{C}(t)_H$, then those groups will enter into quick expansion mode, i.e., no matter which level they are in, those groups will be directly expanded to level 2 when the collision occurs. The HE will continue to count the collision, $\overline{C}(t)$, and if any group's collision amount becomes less than the threshold, $\bar{C}(t)_L$, the level of that group will be directly concentrated to level 0. Both the thresholds $\bar{C}(t)_H$ and $\bar{C}(t)_L$ can be set by the system with different values. From the results of some simulations, we propose $\bar{C}(t)_H$ is 150% of $\overline{C}(t)$, and $\bar{C}(t)_L$ is 50% of $\overline{C}(t)$ in this paper.

C. Coordinate Centralized Control (CCC)

In DOCSIS, all controls and resource management are centralized and handled by the HE. This will cause heavy burden of the HE and relatively light processing at the CM. In this paper, we propose a coordinate centralized control (CCC) scheme to disperse some manipulation power to the edge. CMs will have some intelligence to cooperate with the HE in two prospective works as described in the following.

CMs coordinate with the HE in the contention resolution phase: When stations request priority contention slots initially, it will send request massages during its time slot notified by the MAP and then wait for acknowledgements within the subsequent MAP. In DOCSIS, if the station does not get acknowledgement send by the HE, it means contention occurs and the station just waits for the subsequent MAP to notify it when it can send request message again and stays idle during this period of time. It not only is a waste of the computing power of those CMs but also increases access delay of CMs. In our proposed coordinate centralized control scheme, when stations do not get acknowledgement sent by the HE, it also means contention occurs and these CMs will automatically expand its priority hierarchies into the next level simultaneously with the HE to accelerate the collision resolving speed. And then, the HE will directly send priority-SIDs, including level 1 or level 2 of those collided groups, to notify those CMs, and by coordinate centralized control, CMs have intelligence to send requests in those relative slots via the subsequent MAP.

CMs coordinate with the HE in the dynamic swapping phase: In the contention phase, the HE monitors the collision number of each group of both levels 0 and 1. If the collision numbers of some groups or sub-groups are greater than the high collision threshold, $\bar{C}(t)_H$, of the system, it will invoke the dynamic swapping algorithm to swap with the selected groups in the swapping queue. In our simulation, the HE will notify the relative stations implicitly by indicating swapping flag and the selected sub-groups id through the MAP. When those groups' CMs receive the flag, it will automatically interchange priority-SID with those sub-groups accordingly. The HE needs not to notify the new priority-SID to those CMs. However, both the HE and CMs know the new priority-SID by the dynamic swapping algorithm. We will discuss more details about this algorithm in the next section.

Table 2. Algorithm 2.

```
//Loading statistics phase
Taking statistics of all groups of level 0/1 collision amount of the past twelve cycles
Taking statistics of all groups of levels 0 to 2 hit status of the past twelve cycles
//Dynamic swapping phase
For $i = 0$ to $k - 1$; $k = 16$ {
  If $Group_i \quad \overline{L_i}(t) > \overline{L}(t)_H$ then
  Sorting all groups by loading factor in ascending order at swapping queue $Q = [q_0, q_1, q_2, \cdots, q_{k-1}]$
    For $(a = 0, b = k - 1; a < b)$ {
    If $\overline{L_a}(t) > \overline{L}(t)_H \& \overline{L_b}(t) < \overline{L}(t)_L$ then
    Swap $(q_a, q_b)$
    $a + +, b - -$
    }
    The HE notifies CMs by swapping flags through the MAP
    The HE and CMs swapping simultaneously for those groups before CMs send requests CMs send priority requests to upstream in new group's minislots
  Else
   Taking statistics of collision numbers and hit status of each level
   The HE sends MAP to CMs
   CMs send priority requests to upstream in original group's minislots
}
```

IV. LOADING STATISTICS WITH DYNAMIC SWAPPING ALGORITHM

A. Motivation and Problem Description

Besides efficient collision resolution algorithm, collision avoidance is another important issue in shared medium access environment. How to avoid collisions to support real-time applications especially in heavy loading environment is our objective in this section. DOCSIS has only defined the *truncated binary exponential back-off algorithm* as the collision resolution mechanism, but it did not specify how to avoid collision. This may cause large access delay especially in heavy loading situation. The purpose of Algorithm 1 in the previous section is to resolve contention efficiently. Moreover, to enhance the algorithm, we propose a loading statistics with dynamic swapping algorithm to decrease non-uniform loading distribution in each group and collision avoidance. The HE will monitor not only collision state but also hit status of each group to decide if any group should invoke the dynamic swapping procedure, as will be discussed in this section.

B. Loading Statistics with Dynamic Swapping Algorithm

Since subscribers are non-uniform distribution in CATV networks; moreover, the priority service requirements may be different in business and residential district; as a result, priority services request maybe bursty and variant. For taking the statistics of the collisions and to tune all groups' collision numbers into a near uniform distribution, the HE records all groups' collision numbers and hit status of each level to decide whether to invoke the dynamic swapping before the expansion, since frequent expansion may exhaust upstream bandwidth. The proposed l*oading statistics with dynamic swapping algorithm* is summarized in Table 2, where the following definitions are adopted.

- N: # of greedy stations.
- $\tilde{M}(t)$: Two-dimensional matrix to census the collision number of the past twelve cycles.
- $\tilde{N}(t)$: Two-dimensional matrix to census the level hit status of the past twelve cycles.
- $\overline{C}_i(t)$: Collision # of $Group_i, i = 0$ to 15.
- $\overline{C}_{i,j}(t)$: Collision # of $SubGroup_{i,j}, i = 0$ to $15, j = 0$ to 3.
- $\overline{C}(t)$: # of average collisions of level 0 and 1 at time t.
- $\bar{C}(t)_H$: High collision threshold, $\overline{C}(t) \times$ 150 %.
- $\bar{C}(t)_L$: Low collision threshold, $\overline{C}(t) \times$ 50 %.
- $\overline{S}(t)$: # of average hit status of levels 0 and 1.
- $\bar{S}(t)_H$: High hit status threshold, $\overline{S}(t) \times$ 150 %.
- $\bar{S}(t)_L$: Low hit status threshold, $\overline{S}(t) \times$ 50 %.
- $\overline{L}(t)$: # of average loading of levels 0 and 1 at time t, $\overline{L}(t)$= $\overline{C}(t)^* \, \overline{S}(t)$.
- $\overline{L}(t)_H$: High loading threshold, $\overline{L}(t) \times$ 150 %.
- $\overline{L}(t)_L$: Low loading threshold, $\overline{L}(t) \times$ 50 %.
- l: Set to 12, representing the past twelve cycles.
- k: Set to 16, total group # of level 0.

To monitor all group collision numbers of time t and its history up to the past twelve cycles, we use matrix $\tilde{M}(t)$ and

$M(t-i)$ as shown in the following.

$$\tilde{M}(t)=\sum_{i=0}^{l-1} M(t-i)=$$

$$\sum_{i=0}^{l-1}\begin{bmatrix} m_0(t-i) & m_{0,0}(t-i) & m_{0,1}(t-i) & m_{0,2}(t-i) & m_{0,3}(t-i) \\ m_1(t-i) & m_{1,0}(t-i) & m_{1,1}(t-i) & m_{1,2}(t-i) & m_{1,3}(t-i) \\ m_2(t-i) & m_{2,0}(t-i) & m_{2,1}(t-i) & m_{2,2}(t-i) & m_{2,3}(t-i) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ m_k(t-i) & m_{k,0}(t-i) & m_{k,1}(t-i) & m_{k,2}(t-i) & m_{k,3}(t-i) \end{bmatrix}$$

$$=\begin{bmatrix} \tilde{m}_0(t) & \tilde{m}_{0,0}(t) & \tilde{m}_{0,1}(t) & \tilde{m}_{0,2}(t) & \tilde{m}_{0,3}(t) \\ \tilde{m}_1(t) & \tilde{m}_{1,0}(t) & \tilde{m}_{1,1}(t) & \tilde{m}_{1,2}(t) & \tilde{m}_{1,3}(t) \\ \tilde{m}_2(t) & \tilde{m}_{2,0}(t) & \tilde{m}_{2,1}(t) & \tilde{m}_{2,2}(t) & \tilde{m}_{2,3}(t) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \tilde{m}_k(t) & \tilde{m}_{k,0}(t) & \tilde{m}_{k,1}(t) & \tilde{m}_{k,2}(t) & \tilde{m}_{k,3}(t) \end{bmatrix} \tag{1}$$

$$C(t)_i=\tilde{m}_i(t)+\sum_{j=0}^{3}\tilde{m}_{i,j}(t) \tag{2}$$

$$C(t)=\sum_{i=0}^{k-1}C(t)_i \tag{3}$$

$$\overline{C}(t)_i=C(t)_i/l \tag{4}$$

$$\overline{C}(t)=\sum_{j=0}^{k-1}\bar{C}(t)_j/k. \tag{5}$$

The column 1 of $\tilde{M}(t)$ stands for the amount of the past twelve cycles of all groups' contention number of level 0 at time t, whereas the columns 2 to 5 stand for the amount of the past twelve cycles of all sub-groups' contention number of level 1 at time $t$and denoted in $\tilde{m}_{i,j}$, $j=0$ to 3 to represent four slots of each level 1 subgroup. From this matrix, system will monitor each group's collision numbers of levels 0 and 1 in (2) and all groups' collisions number of levels 0 and 1 in (3). Moreover, to get the average collision number to decide the expansion mode, we have the average collision number of each group of the past twelve cycles in (4); similarly, all groups' average collision number of the past twelve cycles is shown in (5). From $\overline{C}(t)$, we will give $\bar{C}(t)_H$ and $\bar{C}(t)_L$ by the above mentioned definitions. In Algorithm 1 of the previous section, if any group's collision number is greater than $\bar{C}(t)_H$, then system will not assign new comer to that group and will enter dynamic swapping procedure to exchange the heavy collision group, say $Group_a$, with the selective group in the swapping queue, say $Group_b$, according to collision numbers recorded by $\tilde{M}(t)$. If there is no candidate for swapping, then system will ignore swapping and maybe invoke quick expansion mode to resolve high contention in this cycle.

Simulation results show that the access delay of the proposed adaptive scheme does not perform better than that of DOCSIS, especially in heavy offer loads. After some research, we find that in some cases the collision number does not fully reflect system's loading status. For example, with small number of collisions, $Group_i$ may extend to level 2 and stays for a long time because of heavy loading. In such a case, even collisions of $Group_i$ is smaller than $\bar{C}(t)_L$, but it is not suitable for either swapping or concentration. To compensate those exceptions, we introduce another two-dimensional matrix, $\tilde{N}(t)$ as shown in (6), to record the hit status of each level to refine the algorithm. The first column of $\tilde{N}(t)$ stands for every group's hit amount of level 0 from time t to passing eleven cycles. Similarly, the second and third columns represent every group's hit status of levels 1 and 2 from time t to passing eleven cycles, respectively.

$$\tilde{N}(t)=\sum_{i=0}^{l-1}N(t-i)=\begin{bmatrix} \tilde{n}_{0,0}(t) & \tilde{n}_{0,1}(t) & \tilde{n}_{0,2}(t) \\ \tilde{n}_{1,0}(t) & \tilde{n}_{1,1}(t) & \tilde{n}_{1,2}(t) \\ \tilde{n}_{2,0}(t) & \tilde{n}_{2,1}(t) & \tilde{n}_{2,2}(t) \\ \vdots & \vdots & \vdots \\ \tilde{n}_{k,0}(t) & \tilde{n}_{k,1}(t) & \tilde{n}_{k,2}(t) \end{bmatrix} \tag{6}$$

$$S(t)_i=\tilde{n}_{i,0}(t)\times 1+\tilde{n}_{i,1}(t)\times 4+\tilde{n}_{i,2}(t)\times 16 \tag{7}$$

$$S(t)=\sum_{i=0}^{k-1}S(t)_i \tag{8}$$

$$\begin{aligned}\overline{S}(t)_i&=[\bar{n}_{i,0}(t),\bar{n}_{i,1}(t),\bar{n}_{i,2}(t)]\\&=[\tilde{n}_{i,0}(t)/l,\tilde{n}_{i,1}(t)/l,\tilde{n}_{i,2}(t)/l]\end{aligned} \tag{9}$$

$$\begin{aligned}\overline{S}(t)&=[\tilde{n}_0(t),\tilde{n}_1(t),\tilde{n}_2(t)]/k\\&=\left[\sum_{j=0}^{k-1}\tilde{n}_{j,0}(t)/k,\sum_{j=0}^{k-1}\tilde{n}_{j,1}(t)/k,\sum_{j=0}^{k-1}\tilde{n}_{j,2}(t)/k\right].\end{aligned} \tag{10}$$

Through the matrix, the system will monitor each group's hit status of levels 0, 1, and 2 in (7) and all groups' hit status of levels 0, 1, and 2 in (8). Again, to get the average hit status, we have the average hit status of one group of the past twelve cycles in (9) and that of the all groups in (10). After being given the collision number $\overline{C}(t)$ and hit status $\overline{S}(t)$, we shall have the system loading $\overline{L}(t)$, where $\overline{L}(t)=\overline{C}(t)\times\overline{S}(t)$, to completely reflect the system upstream traffic situation. The definitions of $\overline{L}(t)_H$ and $\overline{L}(t)_L$ are similar to those of the collision numbers. Moreover, we replace the decision factor from $\overline{C}(t)$ to $\overline{L}(t)$ in the proposed algorithm to decide the expansion/concentration mode and will show that it performs better in the next section.

C. The Flow Chart and Example

To explain our proposed method more clearly, we depict the flowchart of the proposed algorithm in Fig. 4 and give an example as follows. When a new priority request has been registered by the HE, it will be assigned a 14-bit priority-SID following the rule of *fast identifying and spreading method.* Since the upstream minislots are scarce, we propose adding a swapping phase before the expansion phase so that the system can spread probability of collisions before expanding priority contention slots. To reduce collision resolution time, the expansion mode is divided into *normal* mode and *quick* mode, depending on the loading statistics number compared with $\overline{L}(t)_H$. After the priority request is successfully received by the HE, the CM proceeds to transmission. In concentration phase, the system chooses either normal or quick concentration mode, depending on $\overline{L}(t)$ to reduce concentration time and to save upstream resource. Finally, the next cycle starts.

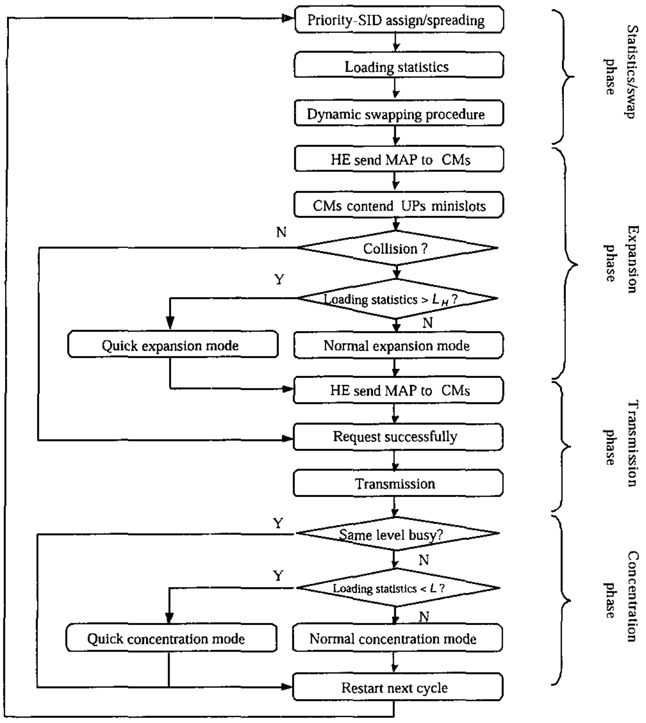


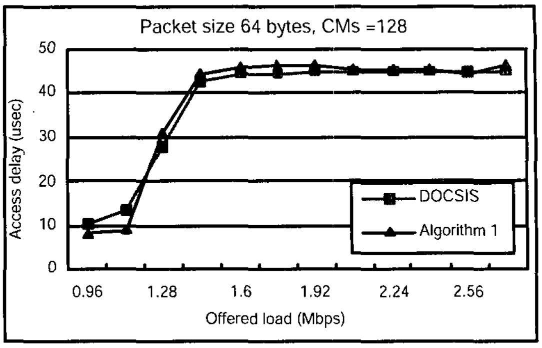
Fig. 4. Flowchart of proposed *fast adaptive expansion algorithm* with collision avoidance method.

Table 3. Simulation parameters.

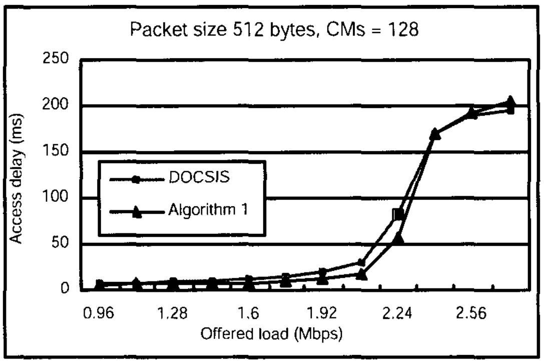
Parameter	Value
Upstream channel capacity	2.56 Mbps
Downstream channel capacity	26.97 Mbps
Minislot	16 bytes/minislot
Number of contention slots in a MAP	40 minislots
MAP size	50 minislots (100%) ~ 2048 minislots (2%)
Maximum number of IEs in a MAP	240
Packet size	64 bytes, 512 bytes
Number of priority CMs	32~256
One way delay	0.5 ms
DMAP time	2 ms
Simulation run	100 sec
Backoff limit (DOCSIS only)	6 ~ 10
Maximum retry (DOCSIS only)	16

V. PERFORMANCE EVALUATION AND DISCUSSION

Access delay and throughput are the two important measures of broadband networks. Access delay is even considered as the key measure in most of the real-time services. In this section, we compare our approach with DOCSIS through the following experiments and point out two topics for further studies. First, we would like to know that besides spreading and quick expansion mechanisms, how the loading statistics and swapping mechanism would affect the performance. Second, how do different packet sizes and offer loads impact the performance in our approach to conform to the requirements of multimedia applications. In practice, we measure the throughput, and access delay of the simulated system, where the throughput is defined as data (in Mbps) that can be transmitted in the upstream channel, and the access delay is the time it takes for a packet to reach the HE successfully after it is initially requested by the station. As most of the subscribers are at the leaves of the HFC networks, we assume that all of them have the same distance to the HE, and the requests have the Poisson arrival rate λ. The simulation parameters are listed in Table 3.



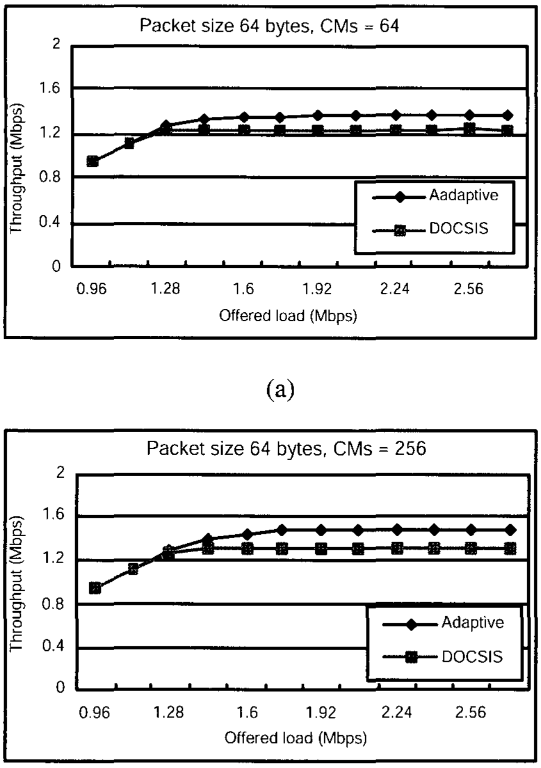
(a)



(b)

Fig. 5. Comparison of the DOCSIS and proposed Algorithm 1 (a) packet size = 64 bytes, CMs = 128, (b) packet size = 512 bytes, CMs = 128.

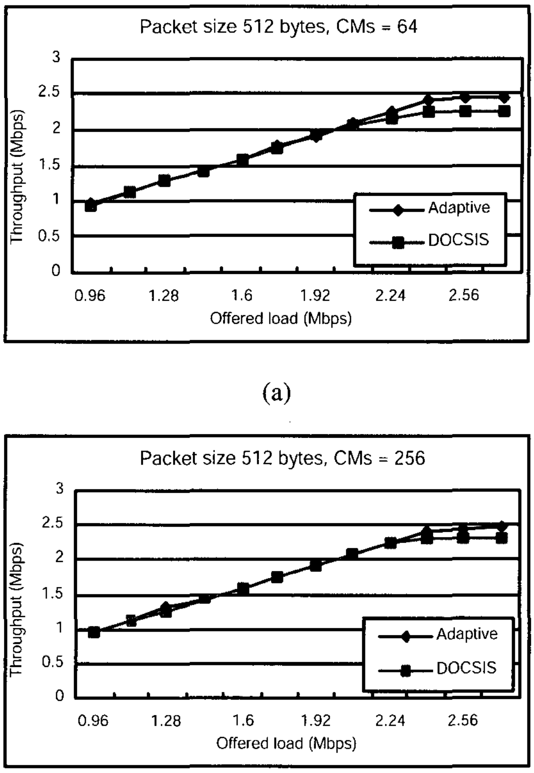
To examine the effects of loading statistics with dynamic swapping algorithm, we perform the following experiment to confirm its refinement. Figs. 5(a) and 5(b) compare the access delay for the proposed adaptive fast expansion method with the DOCSIS without invoking Algorithm 2. To simulate different traffic types of multimedia applications including short and long data packets, we choose packet sizes 64 bytes and 512 bytes to watch its access delay versus variant offered loads. In Figs. 5(a) and 5(b), when offered load is less than 1.12/2.08 Mbps, we have seen the increase of access delay and our method is a bit lower than DOCSIS. While if offered load is over that point, the access delay of both methods will take off sharply and drastic growth thereafter until the offered load reaches 2.72 Mbps. These fig-



(a)

(b)

Fig. 6. Comparison of throughput of small packet versus offered load (a) CMs = 64, (b) CMs = 256.



(a)

(b)

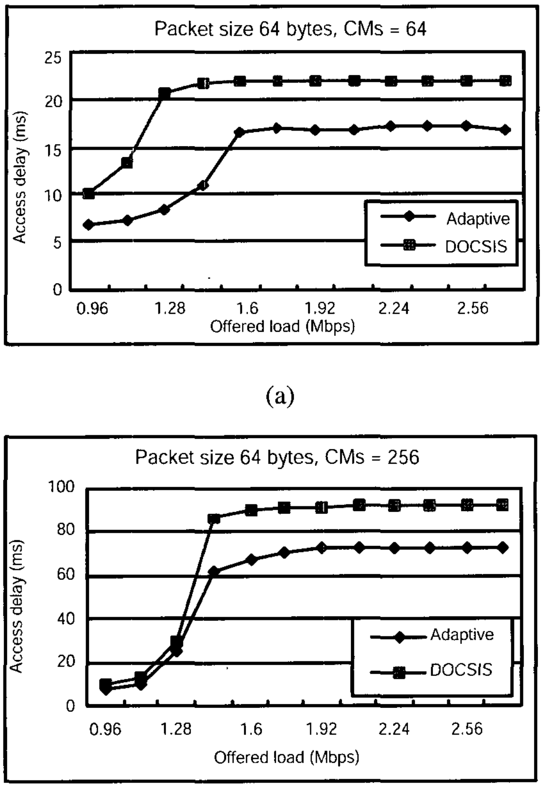
Fig. 7. Comparison of throughput of large packet versus offered load (a) CMs = 64, (b) CMs = 256.

ures also show that our method even exhibit worse access delay than DOCSIS when offered loads are above 2.4 Mbps, if Algorithm 2 is not in place to work with the adaptive fast expansion and concentration algorithm.

The throughput performance versus variant offered loads of small packet comparison of the proposed adaptive fast expansion, loading statistics with dynamic swapping algorithm and DOCSIS is shown in Figs. 6 (a) and (b). In the proposed adaptive scheme, when packet size equals to 64 bytes, both number of CMs equal to 64 and 256 have the throughput about 1.5 Mbps during the steady state, while DOCSIS only shows the throughput of about 1.2 Mbps and 1.3 Mbps, respectively. Therefore the proposed scheme performs much better than DOCSIS under these conditions. Fig. 7 shows the throughput using large packet sizes versus variant offered loads. In both number of CMs, all of the throughput are about 2.3 Mbps during the steady state, which is about 90% of the maximum upstream bandwidth, and the proposed scheme shows better performance than that of the DOCSIS again.

In the following, we will show the influence of packet size, number of CMs, and offered load on access delay and also compare the proposed fast adaptive scheme to DOCSIS. Figs. 8(a) and 8(b) show the access delay of small packet versus variant loading. In Fig. 8(a), the number of CMs are 64, the access delay of proposed method performs pretty low, from 7 ms to 17 ms, and is shown to be less than that of DOCSIS for about 26%. When number of CMs reaches 256 in Fig. 8(b), the access delay of proposed method still performs well from 10 ms to 73 ms and is shown to be less than that of DOCSIS for about 21%. The results of large packet of access delay versus variant loading are shown in Figs. 9(a) and 9(b). With large packet sizes, both our methods and DOCSIS take more access delay then that of small packets. That is because larger packets allocate more data slots, while the upstream bandwidth is limited, and by the definition, the access delay including the time it takes for the packet to reach the HE. Even in this case, our method still performs better than DOCSIS for about 10% to 13% in heavy offered load regions.

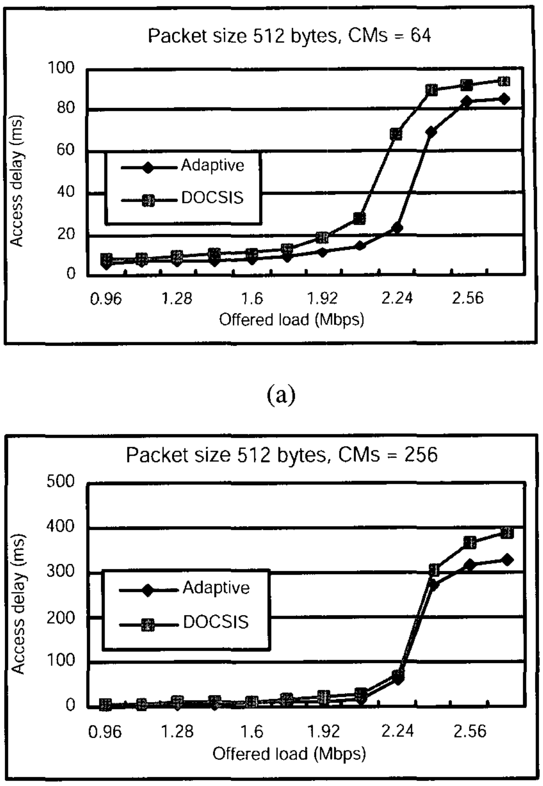
To verify our method in a heavy loading environment, the last experiment is to show how the access delay is affected by packet size, offered load, and variant of CMs. Fig. 10 shows access delay of different packet sizes versus variant of CMs. As shown in Fig. 10(a), with small packet traffic, when the offered load equal to 2.72 Mbps and number of CMs ranges from 32 to 256. The access delay of the proposed method varies from 12 ms to 76 ms and is about 17% less than that of DOCSIS when the number of CMs equals to 256. Fig. 10(b) shows the results as in the same environment as in Fig. 10(a) but with larger packets. The access delay of the proposed adaptive method varies from 43 ms to 327 ms in this case. Even it seems to have a large access delay due to large packet size and extremely heavy offered load, our method still performs about 15% better than DOCSIS with 256 CMs.



(a)

(b)

Fig. 8. Comparison of access delay of small packet versus offered load (a) CMs = 64, (b) CMs = 256.



(a)

(b)

Fig. 9. Comparison of access delay of large packet versus offer loading (a) CMs = 64, (b) CMs = 256.

VI. CONCLUSION

The CATV network has become an ideal backbone to converge heterogeneous network and to provide broadband access to subscribers. In this paper, we proposed an adaptive expansion, loading statistics with dynamic swapping algorithm to support real-time multimedia applications over CATV networks. It is divided into two parts. First, through adaptive fast expansion and concentration mechanism, system could bring down collision numbers due to locality and non-uniform subscriber behaviors. Second, to further improve the QoS performance of the above algorithm, we propose adding loading statistics with dynamic swapping algorithm to progress upstream resource utilization, throughput, and guarantee access delay to fulfill QoS requirements. The dynamic swapping is checked before expansion to save priority contention slots. We also compare the performance of proposed algorithms with that of the DOCSIS. From the simulation results, we conclude that our approach shows a better performance, including access delay and throughput, than that of MCNS DOCSIS in all cases studied.

REFERENCES

[1] A. Gorge, *Residential Broadband*, Second Edition, Cisco Press, 2000.

[2] O. Shlomo, *Broadband Cable TV Access Networks: From Technologies to Applications,* Prentice Hall, 2001.

[3] N. F. Huang and C. A. Su, "CATV-based personal communications network: The architectures and handoff schemes," *IEICE Trans. Commun.*, vol. E82-B, no. 5, pp. 740–750, May 1999.

[4] E. Biton, R. D. Shklarsky, and M. Zussman, "Wireless over CATV: An alternative topology," in *Proc. PIMRC 2004*, 2004, pp. 2889–2894.

[5] E. J. Hernandez-Valencia, "Architectures for broadband residential IP services over CATV networks," *IEEE Network*, pp. 36–43, Jan./Feb. 1997.

[6] P. Brendle and J. Speidel, "Upgrade of coaxial CATV networks for upstream high speed digital communication," *IEEE Trans. Broadcasting*, vol. 44, pp. 353–362, Sept. 1998.

[7] P. Tzerefos, C. Smythe, I. Stergiou, and S. Cvetkovic, "Standards for high speed digital communications over cable TV networks," in *Proc. IEE Conf. Telecomm.*, 1998, pp. 224–229.

[8] Cable Television Laboratories, Inc., "Data-over-cable service interface specifications-radio frequency interface specification," Version 2.0, Dec. 2005.

[9] IEEE 802.14 Committee, "IEEE project 802.14/a draft 3 revision 3," 1998.

[10] M. Ahed and G. Roeck, "IP over cable data network (IPCDN) service," IETF draft, 1996.

[11] ATM Forum Technical Committee, "Residential broadband architecture framework," AF-RBB-0099.000, July 1998.

[12] European Cable Communication Association, "Avenue van kalken 9A," B-1070 Brussels, European Cable Modem v1.0, May 1999.

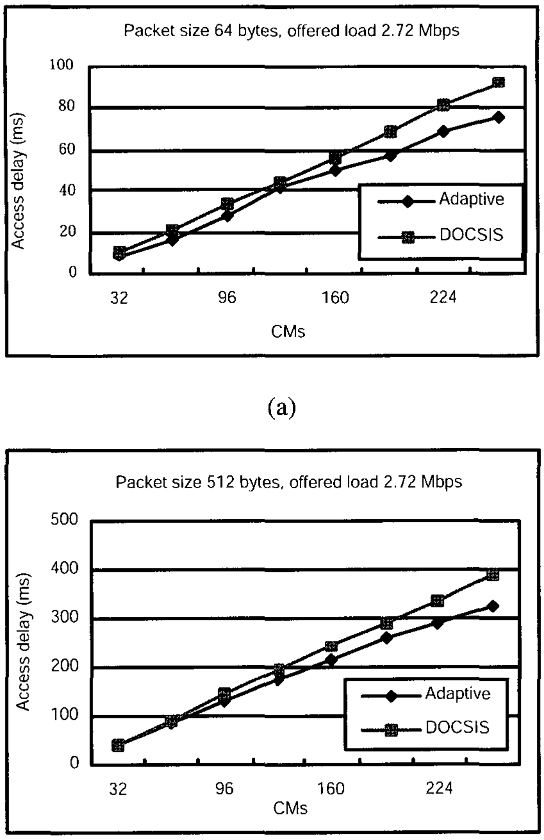
[13] A. Donnelly and C. Smythe, "A tutorial on the digital audio-visual council (DAVIC) standardization activity," *IEE Electron. Commun. Eng. J.*, vol. 9, no. 1, pp. 46–56.

[14] European Telecommunication Standards Institute, "ETS 300800–DVB interaction channel for cable TV distribution systems (CATV)," Digital Video Broadcasting (DVB), 1998.

[15] ITU-T, "Recommendation J.83 series J: Transmission of television, sound programme and other multimedia signals," ITU-T, Apr. 1997.

[16] ITU-T, "Recommendation J.112: Transmission systems for interactive cable television services," ITU-T Pre-published, Mar. 1999.

[17] Y. D. Lin, W. M. Yin, and C. Y Huang, "An investigation into HFC MAC protocols: Mechanisms, implementation, and research issues," *IEEE Commun. Surveys*, pp. 2–13, Third Quarter 2000.



(b)

Fig. 10. Comparison of access delay of different packet size and variant of CMs (a) small packet, (b) large packet.

[18] D. Sala, J. O. Limb, and S. U. Khaunte, "Adaptive control mechanism for cable modem MAC protocols," in *Proc. IEEE INFOCOM'98*, 1998, pp. 1392–1399.

[19] W. K. Kuo, S. Kumar, and C. C. Kuo, "Improved priority access, bandwidth allocation and traffic scheduling for DOCSIS cable networks," *IEEE Trans. Broadcasting*, vol. 49, pp. 371–382, Dec. 2003.

[20] M. Hawa and D. W. Petr, "Quality of service scheduling in cable and broadband wireless access systems," in *Proc. IEEE Inter. Workshop QoS*, 2002, pp. 247–255.

[21] M. D. Corner, J. Libeherr, N. Golmie, C. Bisdikian, and D. H. Su, "A Priority scheme for the IEEE 802.14 MAC protocol for hybrid fiber-coax networks," *IEEE/ACM Trans. Networking*, vol. 8, no. 2, pp. 200–211, Apr. 2000.

[22] Y. C. Chen, S. C. Hsu, T. L. Hsu, and W. S. Hsieh, "The strategies of traffic control for multimedia data transmission with QoS guarantees over CATV network," *IEEE Trans. Consumer Electron.*, pp. 107–117, 1999.

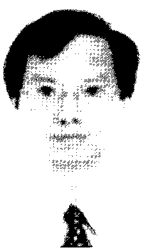
[23] A. A. Elfeitori and H. Alnuweiri, "A MAC protocol for supporting real-time VBR traffic over IEEE 802.14 based HFC access networks," in *Proc. IEEE Canadian Conf. Elect. Computer Eng.*, May 9–12 1999, pp. 197–201.

[24] N. Glomie, F. Mouveaux, and D. Su, "A comparison of MAC protocols for hybrid fiber/coax networks: IEEE 802.14 vs. MCNS," in *Proc. ICC'99*, 1999, pp. 266–272.

[25] D. Sala and J. O. Limb, "A protocol for efficient transfer of data over fiber/cable systems," *IEEE Trans. Networking*, vol. 5, no. 6, Dec. 1997.

[26] N. Glomie, Y. Saintillan, and D. Su, "A review of contention resolution algorithms for IEEE 802.14 networks," *IEEE Commun. Surveys*, pp. 2–12, First Quarter 1999.

[27] M. X. van den Broek, I. B. J. F. Adan, N. Sai Shankar and S. C. Borst, "A novel mechanism for contention resolution in HFC networks," in *Proc. IEEE INFOCOM 2003*, Mar. 30–Apr. 3, 2003, pp. 979–989.



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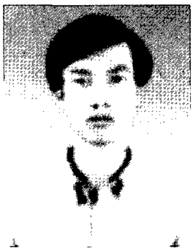

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