A Dynamic Expansion with Coordinate Centralize Control Algorithm over CATV Networks

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Abstract

As broadband multimedia services becoming popular in the past few years, several emerging wired and wireless access technologies have been studied to provide broadband access to subscribers. Since 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 real-time multimedia applications, especially in a heavy traffic environment, becomes a critical issue in modern CATV networks. In this paper, we propose a *Dynamic Expansion with Coordinate Centralize Control Algorithm* for priority traffic over DOCSIS CATV networks to support quality-of-service (QoS) traffic over DOCSIS CATV networks. It intends to fulfill the needs of real-time interactive services, such as video telephony, video on demand (VOD), distance learning, and so on. Through the simulations, the proposed algorithm has been shown to perform better than that of the MCNS DOCSIS.

Keywords: Cable Modem, CATV networks, Contention resolution, DOCSIS, HFC networks.

1. 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 CATV networks, DSL, FTTx, UMTS/CDMA and LMDS/MMDS access networks [1], had been deployed. Among them, Community Antenna Television (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 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 a dynamic expansion with coordinate centralize control algorithm to support QoS in CATV Networks to fulfill the real-time applications over DOCSIS CATV networks.

There are many organizations recommending the 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., the IEEE working group 802.14, the Internet Engineering Task Force (IETF) IP over Cable Data Network Working Group, the ATM Forum Residential Broadband Working Group, the European Cable Communication Association (ECCA), the Digital Audio Video Council (DAVIC), the Digital Video Broadcasting (DVB), Society of Cable telecommunications Engineers (SCTE) and ITU. Both DOCSIS and IEEE 802.14a were developed to facilitate the interoperability between stations and 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 [8]:

- 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

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, distance learning, has been a challenging issue. To resolve this issue, Sala, Limb and Khaunte [9] presented a contention slot allocator (CSA) at the Headend (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.* [10] presented a multilevel priority collision resolution scheme with adaptive contention window adjustment; Hawa and Petr [11] 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.* [12] proposed a multilevel priority-based collision resolution scheme to achieve the capability for preemptive priorities. The authors in [13] also proposed some strategies to support QoS guarantees over CATV networks.

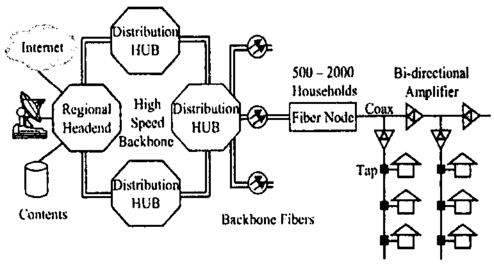

Fig. 1. The architecture of HFC networks.

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 2 presents the overview of HFC networks, including the MAC layer operation, collision resolution protocol (CRP) and QoS. In Section 3, a dynamic expansion with coordinate centralize control algorithm is constructed and studied. The simulation results and discussion was shown in Section 4. Finally, we make a brief conclusion in Section 5.

2. 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 segments, 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 [14]. To reduce implementation complexity and cost, DOCSIS adopts *truncated bi-*

nary 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)
- 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.

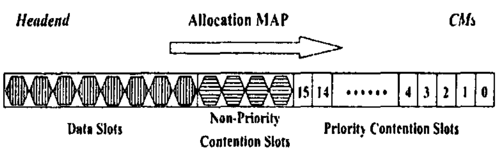

Fig. 2. Assignment of proposed upstream minislots.

3. A Dynamic Expansion with Coordinate Centralize Control Algorithm

3.1 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 dynamic 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.

3.2 Dynamic 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.

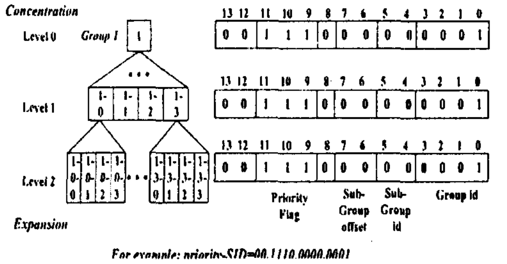

Fig. 3. Structure of group hierarchies and the priority-SIDs.

3.2.1 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 sub-group 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.

3.2.2 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.

3.2.3 Dynamic Expansion and Concentration

To accelerate expansion and concentration speed to reduce contention resolution time, we propose a *dynamic expansion / 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 sub-group 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.

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, $\overline{C}(t)_H$, 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, $\overline{C}(t)_L$, the level of that group will be directly concentrated to level 0. Both the thresholds $\overline{C}(t)_H$ and $\overline{C}(t)_L$ can be set by the system with different values. From the results of some simulations, we propose that $\overline{C}(t)_H$ is 150% of $\overline{C}(t)$, and $\overline{C}(t)_L$ is 50% of $\overline{C}(t)$ in this paper.

3.3 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 work as described in the following.

Table 1. A Dynamic Expansion with Coordinate Centralize Control Algorithm

//Identifying and spreading phase
For each new comer {
  Quickly assigning a priority-SID and automatic spread-
  ing
  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;
//Expansion phase
For each *Group*$_i$, i = 0 to k-1, k=16 {
  If *Group*$_i$ collisions amount is greater **than** $\overline{C}(t)_H$
    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

3.3.1 CMs Coordinate with the HE in 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.

3.3.2 CMs Coordinate with the HE in 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, $\overline{C}(t)_H$, 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.

4. 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, how the spreading and quick expansion mechanisms 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 2.

Table 2. 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	64Byte, 512Byte
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

To examine the effects of proposed algorithm, we perform the following experiment to confirm its refinement. 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. The throughput performance versus variant offered loads of small packet comparison of the proposed dynamic expansion with coordinate centralize control algorithm and DOCSIS is shown in Figs. 4. In the proposed dynamic scheme, when packet size equals to 64 Bytes and CMs equal to 256 have the throughput is about 1.5 Mbps during the steadystate, while DOCSIS only shows the throughput of about 1.2 Mbps. Therefore the proposed scheme performs much better than DOCSIS under these con-

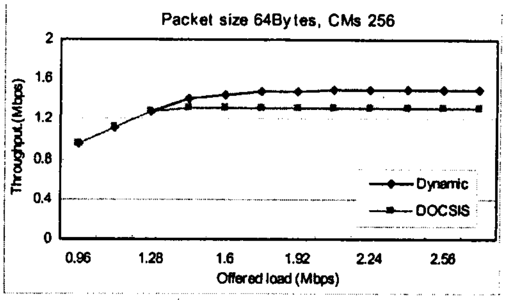

Fig. 4. Comparison of throughput of small packet versus offered load.

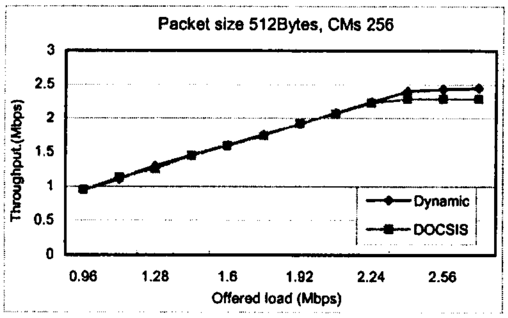

Fig. 5 Comparison of throughput of large packet versus offered load.

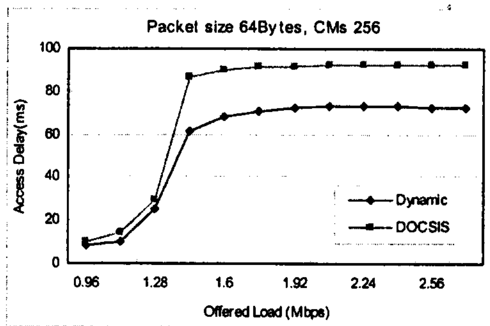

Fig. 6. Comparison of access delay of small packet versus offered load.

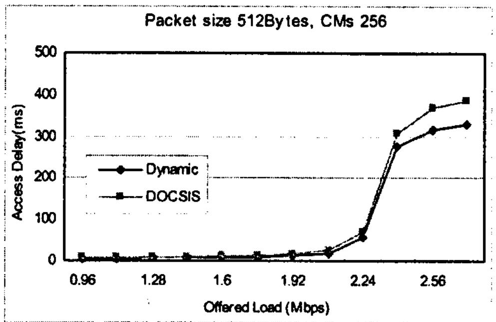

Fig. 7. Comparison of access delay of large packet versus offered load.

ditions. Fig. 5 shows the throughput using large packet sizes versus variant offered loads. In proposed dynamic expansion scheme, 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 and offered load on access delay and also compare the proposed dynamic expansion scheme to DOCSIS. Fig. 6 shows the access delay of small packet versus variant loading. In this experiment, the number of CMs are 256, the access delay of proposed method 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. 7. 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, the access delay of proposed method performs well from 15 ms to 340 ms and is shown our method still performs better than DOCSIS for about 10% to 13% in heavy offered load regions.

5. 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 a dynamic expansion with coordinate centralize control algorithm to support real-time multimedia applications over CATV networks. It is divided into two parts. First, through dynamic expansion and concentration mechanism, system could bring down collision numbers due to locality and non-uniform subscriber behaviors. Second, due to centralize control of DOCSIS, it will cause heavy burden of the HE and relatively light processing at the CM. Therefore, we propose a coordinate centralized control scheme to disperse some manipulation power to the edge to decrease contention resolution time, and guarantee access delay to fulfill QoS requirements. 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.

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