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MAC Alternatives for LMCS/LMDS Networks

by

Mohammad Tariq Ali

*A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of*

Master of Engineering

**Ottawa-Carleton Institute for Electrical Engineering
Department of Systems and Computer Engineering
Carleton University
Ottawa, Ontario
August 20, 1998**

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Graduate Studies and Research acceptance of the thesis

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A b s t r a c t

LMCS (Local Multipoint Communication System) is a bidirectional fixed wireless access technology aims to cater multimedia services to business and residential customers. The nature of supported applications which ranges from highly bursty sources to constant bit rate sources necessitates the use of multiple access techniques for efficient link utilization and QoS guarantees. In this respect TDMA schemes appear at the moment to be the most appropriate choice which can assign bandwidth on demand. CDMA system which gives high capacity gains are presently not considered because of implementation complexity of systems operating with data rate in the 10's of Mbps range.

The focus of this work is to examine and compare the performance of various MAC protocols that are applicable to LMCS networks. DAVIC 1.2 MAC recommendations is the only LMCS specific MAC protocol which provides complete LMCS system engineering solutions, this makes it to be an obvious candidate. The HFC (Hybrid Fiber Coax) networks offer services similar to the LMCS networks, hence HFC-related MACs are also possible candidates. The recently ITU approved DOCSIS (Data Over Cable System Interface Specifications) MAC standard (also called MCNS MAC) is selected for comparison with DAVIC MAC.

Since the study of the upstream channel is comparatively more challenging than that of downstream, we concentrate our study on the upstream performance of both MAC protocols. The performance has been evaluated under homogenous and heterogeneous traffic conditions for noisy and noiseless channels. The reported results include mean-access delay, throughput, probability distribution function of mean-access delay, collision multiplicity statistics, coefficient of delay variation and call blocking probability. Moreover, the effects of dynamic slot allocation schemes and application of ATM scheduling in wireless networks have also been examined.

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List of Acronyms

LMCS	:	Local Multipoint Communication System
LMDS	:	Local Multipoint Distribution System
CMTS	:	Cable Modem Termination System
CM	:	Cable Modem
ATM	:	Asynchronous Transfer Mode
VL	:	Variable Length
MPEG	:	Motion Picture Expert Group
PDU	:	Protocol Data Unit
CS	:	Contention Slot
DS	:	Data Slot
CMS	:	Contention Mini Slot
CRA	:	Collision Resolution Algorithm
RAA		Random Access Algorithm
RAS	:	Random Access System

WWW	:	World Wide Web
RS	:	Reserve Slot
NIU	:	Network Interface Unit
AIU	:	Air Interface Unit
HE	:	Head End
HFC	:	Hybrid Fiber Coax
HOL	:	Head Of Line
VC	:	Virtual Connection
HFQ	:	Hierarchical Fair Queueing
CATV	:	Cable TeleVision
DOCSIS	:	Data Over Cable System Interim Specifications
MCNS	:	Multimedia Cable Network System
URL	:	Universal Resources Locator

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Chapter 1

Introduction

Broadband Access technology has been a research issue for a number of years. It is a gateway to the future (and present) broadband services for example, video-on-demand (VOD), interactive-video games, video-telephony, TV broadcasting, high speed data transfer. The choice of a particular access scheme does not only affect the types and quality of service (QoS) offered by a service provider but also influences other factors such as initial infrastructure cost, operating cost, ease-and-speed of deployment. Major competitive access technologies include Passive Optical Networks (PON), Hybrid Fiber Coax (HFC), Asymmetric Digital Subscriber Line (ADSL), Broadband Satellite Networks and Local Multipoint Communication System (LMCS). The focus of our study in this thesis is LMCS and its multiple access issues. In this respect we examine the performance of the LMCS/LMDS specific, the DAVIC MAC recommendations. For the purpose of comparison we also study the performance of the DOCSIS MAC standard (also called MCNS MAC) which provides similar services in the hybrid fiber/coax environment at comparable capacity.

1.1 Objectives and Motivation

LMCS (Local Multipoint Communication System) is a bidirectional fixed wireless access network, designed to provide broadband services to business and residential customers at

fixed locations. Industry Canada auctioned 1 GHz bandwidth (in the range of 27.35 to 28.35 GHz band) to three companies that are now in the process of deploying LMCS (refer to [7]). The same system is called LMDS (Local Multipoint Distribution System) in the US (U. S. Federal Communications Commission (refer to [2]), which has set aside two blocks of bandwidth: block A includes 27.5-28.35 GHz and 29.1-29.25 GHz, 31.075 to 31.225 GHz and block B includes 31 to 31.075 GHz and 31.225 to 31.3 GHz).

LMCS uses a cellular architecture with a LMCS-hub (or base-station) located at the center of the cell (with a maximum radius of about 5 Km). All communication is carried out through the base-station. As the access link (between the users and the hub) to the base-station is shared among many users, therefore (besides other factors), the choice of the media access control (MAC) is critical for the optimal LMCS system design. The factors considered for the MAC selection are:

- *Link Utilization:* As the wireless link is the most expensive part of the network, therefore, maximization of its utilization is important.
- *Service Support and QoS:* The LMCS MAC should be able to support the same services and Quality of Service (QoS) guarantees as provided by the competitive access networks.

The only LMCS specific MAC available in literature is the one proposed by the DAVIC (Digital Audio Visual Council) [50]. DAVIC suggests a TDMA scheme based on polling, contention and reservation to provide bandwidth on demand. It supports ATM and MPEG-2 transport modes and the associated QoS guarantees.

As HFC networks will provide comparable capacity and services, therefore, we believe that the HFC related MAC protocols are also applicable here (with required adjustments of physical and other parameters). For this reason we have also selected for comparison the DOCSIS MAC standard (recently ITU J-122) for cable networks which is also a TDMA scheme (for details refer to [53]). It uses contention-reservation procedure to assign upstream bandwidth on demand and supports VL PDU, ATM PDU and future defined data PDU.

The main objective of this research is to compare the performance of DAVIC 1.2 MAC Recommendations with DOCSIS MAC protocol. It is done in parallel with a complementary research project which evaluates the performance of the IEEE 802.14 MAC proposals, for comparison purpose [18]. Since the LMCS-hub has no prior knowledge of the upstream transmissions (in particular the contention traffic), hence its performance analysis is comparatively more challenging than the downstream. That is why we focus our study on the upstream performance analysis of the two MAC protocols. The performance is evaluated in terms of mean-access-delay, throughput, collision-multiplicity statistics, probability distribution function of mean access delay, delay-variance and call-blocking-probability (for CBR traffic). The performance of the MAC has been examined both under channel errors and in a noise-free channel environment. The effect of dynamic slot allocation (of contention and data slots) schemes on the performance metrics (mentioned above) has also been considered. Besides, the application of ATM scheduling in wireless networks (with Hierarchical Fair Queueing as an example) has also been studied.

1.2 Major Contributions

DAVIC 1.2 recommendations provide a complete solution for LMCS system engineering which makes its MAC to be an obvious choice for LMCS. However, HFC-related MAC protocols (i.e., IEEE 802.14 MAC proposals and DOCSIS MAC standard) are also relevant because LMCS system aims to cater for services similar to HFC systems. The motivation was to compare the performance of the DAVIC MAC with that of DOCSIS MAC standard and with IEEE 802.14 MAC proposals. Since no previous work on the performance evaluation of DAVIC MAC and DOCSIS MAC is available in the literature, hence, this work is a significant contribution for the LMCS system design. Our work can be categorized in the following areas:

- Developed two separate simulators to analyze the performance of the DAVIC and DOCSIS MAC protocols.
- A number of traffic models were built to study the performance of the two protocols.
- Performance evaluation of the two MAC protocols under wide variety of homogeneous and heterogeneous traffic conditions.
- Examined the effects of channel errors on the MAC performance.
- Suggested an adaptive CS/DS ratio scheme.
- Effect of fixed and dynamic slot allocation (of contention and data slots) schemes on the MAC performance.
- Implemented ATM scheduling (proposed for wireline networks) in wireless system (for example LMCS) and its performance study through simulations.

1.3 Thesis Organization

This thesis is organized in three sections: the first section (chapter 1 and 2) describes the LMCS system and the role of media access control, the second section (chapter 3, 4 and 5) explains the components of a MAC, traffic models and the candidate MAC protocols and the last section (chapter 6 and 7) discusses the performance of the DAVIC and DOCSIS MAC protocols and finally ends with conclusions and future recommendations.

Chapter two discusses the LMCS systems (similar discussion can be found in chapter 2 of [18]), the role of media access controls and the related performance issues.

In chapter three we talk about the various components of MAC which includes the Collision Resolution Algorithms (CRA) (similar discussion can be found in chapter 3 of [18]), the base-station scheduling and Contention and Reserve Slot Allocator.

Chapter four begins with the discussion of DAVIC MAC recommendations and then we describe the DOCSIS MAC standard and IEEE 802.14 MAC proposals (similar discussion can be found in chapter 4 of [18]).

Selected traffic models for the MAC performance evaluation is described in chapter 5 (similar discussion can be found in chapter 5 of [18]).

In chapter 6 we discuss in detail the simulation results of DAVIC and DOCSIS MAC protocols.

Conclusions and suggestions for future work are given in chapter 7.

Chapter 2

Local Multipoint Communication System - An Overview

2.1 Broadband Fixed Wireless systems

The idea of outdoor broadband wireless distribution systems where the users are in fixed locations is not entirely new. We are familiar with the broadcast of television where the use of radio spectrum either with terrestrial radio transmission or via satellite systems has provided broadband access to televised broadcast media. These systems have a range of tens of thousands of kilometers, and have achieved a penetration rate of billions of residential subscribers across the globe. Another example of broadband fixed wireless access which is comparatively a recent development is geographically localized technology, the wireless LAN.

Conventional local access networks (twisted pair cable) could only carry voice and low speed data. As the demand for high speed data increased with time various broadband access networks were introduced such as HFC, ADSL on copper twisted pair, Fiber to the curb (FTTC), etc. (for an overview refer to [9], [10]). Within this decade Telecommunication researchers in UK and in North-America explored the feasibility of using the millimeter frequency band(28 GHz and higher) for broadband fixed wireless communication systems as an alternative to the conventional wireline broadband access networks. The

major issues related to the system architecture, economically available RF support technology, improvement of coverage and cost effective distribution, must be resolved before its widespread implementation.

LMCS, Local Multipoint Communication Systems, is a broadband fixed wireless access system to provide bidirectional broadband information and entertainment services to subscribers in fixed locations(i.e., homes, offices, hotels, etc.) through millimeter wave radio technology and small fixed antennas. Some of the typical services (refer to [4]) which LMCS can provide are; Delivery of two way high speed data, Broadcast of video, Video on demand service, Telephony.

2.1.1 Advantages of LMCS

Few major advantages of LMCS over the competitive access technologies are discussed as follows (refer to [7]).

1. Low Infrastructure Costs: Infrastructure costs are relatively low in LMCS compared to conventional wireline systems where extensive build-out of infrastructure is required before commercial services can be launched.

2. Ease-And-Speed Of Deployment: Deployment of cable and fiber systems is difficult in certain areas where installing in-ground infrastructure is undesirable (due to existing building and infrastructure in place), impractical (due to terrain). LMCS can provide similar access bandwidths and a two way capability without trenching streets and yards.

3. Faster Realization of Revenues: The speed of deployment comes with faster recovery of investments and profits.

4.Quick Response to Growing Market: Because of high speed deployment the investors can quickly respond to the growing market demands.

5. Mobility Capabilities: If either mobile or portable services are required, wireless technology offers unique capabilities over conventional systems.

2.1.2 Spectrum Allocation

In the US, the Federal Communications commission (FCC) set aside two blocks of bandwidth for LMDS as described in [6]. (Block A has a total bandwidth of 1150MHz: 27.5 to 28.35 GHz, 29.1 to 29.25 GHz, 31.075 to 31.225 GHz and block B has a total bandwidth of 150MHz: 31 to 31.075 GHz and 31.225 to 31.35GHz). In Canada, LMCS services in the 27.35 to 28.35 GHz range have been granted to three companies that are now in the

process of deploying networks. Four other blocks of 500 MHz have been reserved for future use.

Figure 2-1: LMDS Band Allocation (Local Multipoint Distribution Service)

2.1.3 Network Architecture

LMCS/LMDS network architecture can be broadly categorized into the following major areas (for details refer to [7]).

1. Base-station equipment: All communication is done through the base-station which performs the role of gateway between wireline and wireless network. Its major function include: multiplexing, mapping, compression, error detection, encoding/decoding, modu-

lation/demodulation and media access control. The base-station may or may not have switching facilities.

2. Radio frequency (RF) equipment: It consists of a pair of transmitters and receivers or a transceiver and antenna system. In order to minimize the attenuation problem, the RF elements are desired to be close to the antenna.

3. Customer premises equipment: It contains an antenna system, transceiver and a Network Interface Unit (NIU). The transceiver down-converts the received signal to an IF level.

4. Network management system: This manages the whole LMCS network (or possibly a limited number of hubs) from one point. Hence the network can be managed efficiently and at low cost. It performs the following functions; Fault management, Configuration management, Accounting management, Performance management, Security management.

2.1.4 Major Challenges For LMCS

The major impediments in the successful deployment of LMCS are (refer to [3], [5], [8]):

- Propagation impairments and Coverage
- Cost effective distribution infrastructure
- Development of RF (radio frequency) technology

Propagation characteristics of millimeter waves require that transmission should be LOS (Line Of Sight), this means the coverage area is small. Consequently we have more number of cells for a given area and therefore increased number of hubs and distribution infrastructure. This makes the provision of cost effective distribution and coverage to customers in varied geographical areas more challenging. Besides, to compete with the alternative broadband access technologies (for example HFC) low cost RF and antenna technology development is required.

2.1.5 Backbone Alternatives

The choice of the backbone network depends on the supported applications and the cost of infrastructure (for details refer to [19]). The available alternatives may include:

- Star-Based Point-to-Point Configuration
- Digital SONET rings
- Hybrid Fiber-Radio Configuration

In **Star-based configuration**, each hub is directly connected to the central hub through fiber links. This scheme is suitable for a small number of LMCS hubs.

In **digital SONET rings configuration**, a fiber link emanates from the central hub connecting a number of hubs and terminates at the central hub. This alternative is more reliable (and possibly less expensive) than the Star-based configuration.

In **hybrid fiber-radio configuration**, a hub with few customers (initial growth stage) is connected through radio link to another hub which is connected to a SONET ring. As the user population grows at a radio connected hub, it may be shifted to the SONET ring configuration. Such a scheme provides modular and cost effective solution.

2.2 The Role of Media Access Control

The role of the MAC in a LMCS system is to control the active users transmissions in order to maximize link utilization and provide QoS guarantees. To achieve high throughput in a multi-service network, the selected MAC should be able to allocate bandwidth on demand dynamically to the active users. It also requires a flexible MAC protocol capable of transporting information in Synchronous Transfer Mode (STM), Asynchronous Transfer Mode (ATM) or Variable Length (VL) PDUs (e.g., IP, 802.3 packets).

2.3 Performance Parameters

The following parameters describe the performance of a MAC protocol.

1. Access delay: It is defined as the elapsed time between the instant of time that a message is passed to the MAC layer and when the last bit of it is received by the LMCS-hub.

2. Throughput: It is the ratio of the aggregate successful transmissions to the total transmissions attempts.
3. Collision Multiplicity: The number of collided users in a time slot.
4. Delay Variation: The difference in the access delay experienced by a packet relative to the mean access delay.
5. Coefficient of Delay Variation: The ratio of standard deviation to mean-access delay.

Through this study we identify the key set of MAC protocol features that results in significant performance gain. The DAVIC 1.2 MAC recommendation uses ATM transport mode and supports both contention-reservation and contention mode (immediate data transfer) of operation. It uses contention slots for initial and additional bandwidth requests. Both the reservation and contention slots are of same size (68 bytes). The DOCSIS MAC protocol can carry ATM PDUs, VL PDUs and Future defined PDUs. It can also operate in contention-reservation or contention mode. The contention slots are used for initial bandwidth requests and piggy-backing may be used for addition bandwidth requirements. The smallest unit of transmission is mini-slot which can be combined to form Contention Mini-Slot (CMS), ATM PDU or VL PDU. These differences in the two protocols affect the above mentioned performance metrics.

Chapter 3

MAC Components

A MAC protocol is a combination of several entities each performing a defined function. These entities coordinate with each other in an organized manner (defined in MAC) to carry out the job earmarked for MAC layer protocol. The major components of the MAC protocol include the collision resolution algorithm, data cell scheduler and contention-reserve slot allocator. The behavior of these components has a significant bearing on overall MAC performance which may be judged in terms of access-delay, delay variation, fairness and robustness.

Although a number of CRAs has been proposed in literature, we focus our study here on those CRAs which are part of IEEE 802.14 MAC proposals and DOCSIS MAC standard. We will also discuss few schemes through which the performance of these CRAs can be improved (but at the cost of added complexity). Scheduling schemes that can provide QoS guarantees and fairness among the active connections are deemed more appropriate for LMCS networks. For these reasons, we examined the application of a hierarchical scheduling scheme (proposed for wireline networks) in wireless networks (for example, LMCS). Furthermore, a simple adaptive contention-reserve slot allocation scheme which can be used to improve the performance of MAC protocols is described at the end.

3.1 Collision Resolution Algorithms

The candidate multiple access protocols for the LMCS system employ random access for the station's registration and upstream bandwidth requests (for example, the DAVIC 1.2 MAC recommendations). The use of random access is the most appropriate for such purposes but has an inherent drawback; i.e., when two or more stations' happen to transmit at the same time then collision occurs. Since the collision resolution process consumes resources, therefore, the throughput of the random access system decreases. In addition, the registration and bandwidth request delays also increase. Hence, a Collision Resolution Algorithm (CRA), plays a key role in RAS and is one of the major differences among the performance of various contention/ contention-reservation based MAC protocols.

A collision resolution algorithm (CRA) can be defined as an algorithm (described in space and time) that organizes the retransmission of collided packets in such a way that every packet is eventually transmitted successfully with finite delay and moreover, all transmitters (or at least all those to which this is relevant) become aware of this fact.

In this section we will focus on the study of CRA considered in the DAVIC, IEEE802.14 and MCNS MAC protocols and their possible variations, for more details on CRA refer to [22], [23], [33], [34], [57], [63], [64].

3.1.1 Splitting Algorithms

The idea behind these algorithms is to divide the collided users into Q sub-groups (where the variable Q may range from 2 to any required/reasonable integer value). Each station involved in collision throws a die which has Q faces, the station/stations flipping 1 will transmit first; those flipping 2 will transmit in the next slot after the collision (if any) among those who flipped 1 has been resolved and so on. Since, this process of splitting the collided users can be easily visualized through a Q -ary tree (especially the blocked access), or a stack (especially the free access), these algorithms are also identified by these names. For a detail and excellent review the reader may refer to [23],[57], [63], [64].

Based on channel access protocol, the splitting algorithms can be divided into the following two classes:

1. Blocked Access Algorithms
2. Free Access Algorithms

In the following section we explain the splitting algorithms, for its performance analysis and implementation overview refer to [20], [21], [25].

3.1.1.1 Blocked Access Algorithms

Also referred to as tree search algorithm. New packets are not permitted into the system while a collision resolution process is underway. A Blocked access algorithm is explained with the help of the following example.

3.1.1.1.1 Binary Tree Algorithm

When the feedback message is binary i.e., Collision/No Collision, the tree search algorithm is termed a binary tree algorithm. This algorithm is explained with the help of figure 3-1.

- The integer values in the circle shows the number of collided users.
- A collision occurs in slot 1. At this point it is neither known how many users nor who are the users that collided in this slot.
- Each of the colliding users flip a coin and those that flipped 0 transmit in slot 2. Since in this example we have a binary blocked access algorithm (splitting parameter $Q = 2$), therefore, no newly arrived packet is allowed to be transmitted while the collision resolution (of a previous collision) is in progress, hence only that users that collided in slot 1 and flipped 0 transmit in slot 2. The collision resolution process and blocking of new packets is controlled through a broadcast channel from the central hub.

Figure 3-1: Example of the Binary Tree Protocol Operation

- Another collision occurs in slot 2 and the users involved in that collision flip a coin again. All the colliding users of slot 2 flipped 1 and therefore slot 3 is idle.
- The users that flipped 1 in slot 2 transmit again in slot 4, resulting in another collision and forcing the users involved in it to flip a coin once more.
- One user flips 0 and transmit (successfully) in slot 5 causing all users that flipped 1 in slot 4 to transmit in slot 6.
- As there is only one user in slot 6, therefore, the transmission is again successful.
- Now that the collision among all users that flipped 0 in slot 1 has been resolved, the users that flipped 1 in that slot transmit in slot 7. Another collision occurs and the users involved in it flip a coin.
- Another collision is observed in slot 8, meaning that at least two users flipped 0 in slot 7.
- The users that collided in slot 8 flip a coin and, as it happens, there is a single user that flipped 0 and it transmits successfully in slot 9.
- The users that flipped 1 in slot 8 transmits in slot 10. As there is only one such user therefore it transmits successfully.
- Finally, the users that flipped 1 in slot 7 transmits in slot 11. In this case there is no such user therefore the slot is idle.

- The time span from the slot where an initial collision occurs up to and including the slot from which all transmitters (or at least all those to which it is relevant) recognize that all packets involved in the above collisions have been successfully received is known as Collision Resolution Interval (figure 3.1).

3.1.1.2 Free Access Algorithm

It is also referred to as stack algorithms. New packets can be transmitted while the collision resolution process is in progress. The algorithm is explained as follows.

3.1.1.2.1 Free- Access Stack Algorithm: (splitting parameter $Q=2$)

The algorithm is explained as follows (also refer figure 3-2).

- In each slot the stack is popped, and all the users that were at the top of the stack transmit their messages along with the new users (if any). In the case of a collision, the stack is pushed with the users that flipped 1 and then pushed again with those that flip 0.
- The users that flip 0 remain therefore at the top of the stack and transmit along with the new users in the next time slot.
- In figure 3-2a we see no collision when the popped user transmits along with the new user (i.e., the sum of popped users and the new users is less than or equal to 1). Hence, the stack size reduces.

- In figure 3-2b, there were at least two users (i.e., X_0 plus the new users were equal to or greater than 2) when the stack was pushed and the users in that transmitted along with the new users (if any). A collision occurred and the stack size increases.

Figure 3-2a: No collision

Figure 3-2b: Two Users Collided

Figure 3-2: A stack collision resolution Algorithm with binary feedback splitting parameter $Q=2$

3.1.1.3 The Modified Binary Tree Protocol: (The Ternary Tree Protocol)

We can see in figure 3-1 that a collision in slot 2 is followed by an idle slot (slot 3). This implies that in slot 2 all users (and there were at least two of them) flipped 1. Therefore, all those users which transmitted in slot 2 will now transmit in slot 4, although it is obvious that this will generate a collision that can be avoided. The modified binary-tree protocol (suggested in [57]) eliminates such avoidable collisions by letting the users that flipped 1 in slot 2 (figure 3-1) to flip a coin before transmitting in slot 4. Since in the binary tree algorithm the users receive either a collision or No Collision message, therefore, the users can't identify the idle slots. In the modified binary algorithm, i.e., the ternary tree algorithm, the feedback message also contains, in addition to Collision and No Collision, the Idle slot message which gives users a chance to skip the for sure collision slots. Hence, the slot in which an avoidable collision would occur is skipped as shown in figure 3-3.

Figure 3-3: Example of the modified Binary Tree Protocol Operation

The ternary tree algorithm gives the best efficiency in the absence of feedback errors. The deadlock occurs in case of feedback errors as shown in figure 3-4, where E and C represent empty slot and Collided slot respectively. Slot 1 is idle but because of the feedback errors received as collision by the contending users.

Figure 3-4: The reaction of the ternary tree search CRA to Feedback Errors

Such deadlocks can be resolved, for example, by allowing only a maximum of successive empty slots and then forcing a CRI termination, but then the advantages of this more elaborate scheme starts to become insignificant.

3.1.1.4 Variations in tree algorithms

3.1.1.4.1 Enabled Interval Transmission

In blocked-access (tree-search) RAAs all new arrivals during a CRI can only attempt their first transmission as soon as the CRI terminates (such a scheme is termed the obvious first transmission rule) as shown in figure 3-5, below.

Figure 3-5: The obvious first transmission rule for blocked access tree-search algorithm

As it is apparent from figure 3-5, with the obvious first transmission rule, the number of packets transmitting in the first slot of a new CRI, and hence its length, is positively correlated to the length of the previous CRI. Hence, large CRIs are followed by large CRIs as well, a condition that may persist for long time resulting in low system performance. Per-

formance may increase (as it indeed does), if we de-couple the arrival axis from the transmission axis (such a scheme is termed the non-obvious first transmission rule and explained in [57] and [23]) as shown in figure 3-6, below.

Figure 3-6: The non-obvious first transmission rule for blocked access tree-search algorithm

Only those packets that arrived during the next “delta” time interval are accepted into the system. The parameter “delta” can be selected for optimum system performance. Such a scheme requires the monitor station (e.g., base-station) to notify the stations of not only the end of the CRI, but also of the next arrival interval to be “inspected”; the so called enabled interval. So the splitting in subgroups can be done not only by flipping dice, but also by appropriately splitting the enabled interval (or possibly the hybrid of the two). This much harder to implement version of the tree-search algorithms can achieve absolute

first-in-first-out (FIFO) packet transmission ordering, in contrast to the quasi-FIFO service of the dice splitting, tree-search RAAs, and the quasi-LIFO service of the stack RAAs.

3.1.1.4.2 Dynamic Q-ary Tree-Algorithm

The present technology does not allow us to determine the number of collided users. If such a technology can be devised in future then a Dynamic Q-ary Tree algorithm (refer to [57]) may prove to be the most efficient collision resolution algorithm. In such an algorithm the collided users will be split into sub-groups based on the information of number of collided users. This can be explained with the help of figure 3-7, below.

Figure 3-7: Dynamic Q-ary tree algorithm

In slot 1 there are three users who collided, therefore, we need at least three slots to transmit these three packets successfully. Hence, the collided users are divided into 3 sub-groups. By chance the three collided users happens to select slot 2, 3 and 4, so the colli-

sion is resolved. Again in slot 6 we have a collision and this time 5 users collide. Since, the base-station knows that there were 5 users who collided in this slot, therefore, it will direct the collided users to split into 5 sub-groups. This is expected to reduce the CRI (and the delays associated with long CRI). Even without the knowledge of the collision multiplicity, it has been observed that by varying the value of Q dynamically better performance can be achieved than for a fixed Q value (for more details refer to [32]).

3.1.1.4.3 Capture Effect

In a wireless environment sometimes even in the case of collision, a packet which has strong signal power, because the user is close to the base-station, gets through. This effect is called the capture effect. In such cases (refer to [24] and [57]) the feedback message would be “No Collision” which would be misleading for the users whose packet did not get through. Therefore, the “No Collision” feedback message should include the user identity. In this way the users who did not receive the positive feedback would try again in the next slot and the number of collided users would be one less due to capture effect (the number of collided users would further decrease if the capture effect continues). Consequently the throughput of the system increases and the length of the collision resolution interval decreases (i.e., mean packet transmission delay decreases).

3.1.2 Truncated Binary Exponential Back-off Algorithm

3.1.2.1 Binary Exponential Back-off Algorithm

This has been widely used in ALOHA family of random access system (RA) and is the standard for IEEE 802.3 Ethernet LANs. The philosophy behind the exponential back-off algorithm is to spread farther and farther apart in time the retransmission of collided stations, since repeated collisions may be an indication that the traffic load in the network has increased. The algorithm is explained below. (For details see [57], [64], [23])

- A station transmits a packet in the first available contention slot after the packet arrives at the station.
- The station waits for the feedback of transmission.
- A station that has experienced m collisions selects randomly to re-transmit after 1 to 2^m slots. The variable m ranges from 0 to an upper limit M (commonly $M = 10$).
- If m has reached the upper limit M the station terminates transmission attempts and discards the packet.
- In case of collision, the collided users are requested to wait and opportunity is given to new users to transmit first. Hence, exponential back-off algorithm is not fair in a sense that it can result in quasi-last-in-first-out (quasi-LIFO) packet transmission order.

- This algorithm becomes unstable when the load is increased and stability can only be achieved at the cost of packet loss.

3.1.2.2 p-persistence

As mentioned above the binary exponential back-off algorithm does not provide fair treatment to collided users and new-comers. Furthermore, the algorithm becomes unstable under high load conditions. These effects can be minimized by changing the entry persistence (for details read [57],[63],[64], [22], [30], [31]). In this scheme the collisions are resolved by limiting the contending users to transmit in the next contention slot with probability p .

This scheme can be implemented in frame based protocols as follows. Each station selects a slot for transmission from the range provided by the central coordinating authority (base-station). This range is changed dynamically depending on the load conditions to stabilize the algorithm (the estimation of p is discussed in section 3.1.2.3). This scheme provides no upper bounds on delay and delay variations are high as compared to the splitting protocols. The maximum achievable throughput is given by (see [64], [30], [31], [23]),

$$\eta_{persistent} = P_s = N_a \times p \times (1 - p)^{(N_a - 1)} \quad (3.1)$$

Where N_a represents the number of contending users in a particular contention slot. As the user population increases the bound(Eq. 3.1) asymptotically approaches to $1/e$ (when

$p = N_a$). The stability can only be achieved if the user population can be estimated and the value of p is changed accordingly. Pseudo-Bayesian algorithm provides one way to estimate the user population and is described in next section.

In DAVIC, the p -persistence algorithm can be implemented by broadcasting the retransmission probability at the start of each frame. Whereas, in MCNS which employs truncated binary exponential back-off algorithm for collision resolution, the p -persistence algorithm can be implemented as follows. It uses two windows, data back-off start (DBS) and data back-off end (DBE). When a station has data to transmit, it selects the slot randomly from a range of 2^{DBS} and transmit in that slot. In case of collision it increases its window size to $2^{(DBS+1)}$ until it reaches the maximum window size of 2^{DBE} and retransmits. This process is repeated until the packet is transmitted successfully or the maximum number of retries has reached, in the later case the packet is discarded. The p -persistence algorithm can be emulated in MCNS MAC by setting the DBS and DBE to the same value and this value is the estimated p value.

3.1.2.3 Pseudo-Bayesian Algorithm

Many algorithms which estimate the backlogged users population are available in the literature ([64], [23], [30], [31]). The stability of the binary exponential algorithm may be guaranteed by dynamically changing the value of retransmission probability,

$p = \min\left(1, \frac{1}{\hat{N}_a^k}\right)$ where $\hat{N}_a^k$ is the number of back-logged stations in slot k . The exact

value of $\hat{N}_a^k$ can not be known and Rivest' pseudo-Bayesian algorithm is used to estimate this value ([64], [23],[31]). In this scheme the new users join the collided users which jointly forms the total backlogged users and transmit with probability p . Hence, if $\hat{N}_a^k$ is the number of backlogged users at the start of a contention slot 'k' then the number of users transmitting in that slot is given by probability ' $\hat{N}_a^k \cdot p$ ' and the probability of the successful transmission is ' $\hat{N}_a^k \cdot p(1-p)^{\left(\hat{N}_a^k-1\right)}$ '. The number of backlogged users in slot '(k+1)', $\hat{N}_a^{k+1}$, can be estimated as follows:

$$\hat{N}_a^{k+1} = \begin{cases} \max\left(\lambda, \hat{N}_a^k + \lambda - 1\right) & \text{for idle or success} \\ \hat{N}_a^k + \lambda + (e-2)^{-1} & \text{for collision} \end{cases} \quad (3.2)$$

The contribution from new arrivals is guaranteed by adding λ to the previous backlogged users and using the maximum operation. In case of successful and idle transmission 1 is subtracted to account for the successful departure and minimizing $\hat{N}_a^k$ when too many idle slots respectively. Furthermore, adding $(e-2)^{-1}$ has the effect of increasing $\hat{N}_a^k$ when too many collisions occurs. In equation 3.2, the arrival rate λ is also not known and is required to be estimated.

3.1.3 Comparison of Collision Resolution Algorithms

A brief comparison of binary exponential and Tree algorithm is given in the following table. For details please refer to [20],[23],[28],[30],[31] and [57] and [64].

S.No.	Binary Exponential Backoff Algorithm	Binary Tree Search Algorithm
1	Simple to implement	Implementation complexity increases for improved performing tree algorithms.
2	Both central and distributed control schemes can be implemented	Collision resolution process is controlled by the base-station
3	Widely used in CSMA-CD, hence cheap VLSI chips are available.	This has not been used in commercial product hence technology development would require high costs.
4	In terms of access delay the performance is close to splitting algorithms.	Access delays have not significantly different than binary exponential backoff.
5	The maximum achievable throughput is close to 37%.	With variations in tree algorithm throughput can be increased to approximately 48% but at increased implementation complexity.
6	Such algorithms are unstable and stability can be guaranteed by dynamically varying the retransmission probability.	These protocols are stable under all load conditions.
7	High delay variation which can be reduced by using p-persistence with soft blocking.	Moderate delay variation.
8	Low collision multiplicity.	High collision multiplicity in blocked tree algorithms.
9	No upper bounds on delay.	Bounds for maximum delay are available.
10	P-persistence with soft-blocking is more reliable and efficient than the p-tree algorithms under noisy channel.	In addition to Collision/ No Collision feedback, the tree algorithm requires to broadcast/ multicast the group identification number with each contention slot. This degrades its performance in the presence of channel errors.

3.2 LMCS-Hub Scheduling

LMCS networks will support a wide variety of services with differentiated QoS requirements. As such the role of the scheduling algorithm becomes increasingly important. Scheduling algorithms are usually not specified as part of the MAC protocol and the choice is left to the vendor. According to ATM Forum classifications, we can divide the broadband services in real-time (rt) and non-real-time (non-rt) applications (refer to [44] and [45]). The rt-applications can be further divided into constant bit rate (CBR) and real-time variable bit rate (rt-VBR) categories. The non-real-time applications can be further divided into non-real-time variable bit rate (non-rt-VBR), available bit rate (ABR) and undefined bit rate (UBR) categories. Real-time applications can afford a limited delay while the non-real-time applications require a minimum throughput guarantees. The choice of the scheduling scheme should be such that it can satisfy the two conflicting requirements without wasting the link resources. Since a LMCS hub is supposed to provide services similar to wireline network, therefore we can possibly use the same scheduling schemes. This will provide cheap hardware for LMCS which is being used in wireline networks (for excellent review refer to [35], [49]).

3.2.1 Difference between Wire-line & Wireless Scheduling

Although there are many similarities between scheduling in wireline and wireless networks there are few major differences which require separate treatment.

3.2.1.1 Scheduling in Wireline Networks

In a wireline network, each user may have a dedicated link to the switch and the link/ links between switches is shared among the active users as shown in figure 3.8. The data of all users is queued at the switch for transmission and hence the switch has knowledge of the user queue size. This is important in the provision of the committed QoS.

Figure 3-8: A typical Wireline network

3.2.1.2 Scheduling in Wireless Networks

However, in the wireless network the access link to the base-station as well as the link/ links between switches is shared among the active users as shown in figure 3.9. In the wireless network the users' buffers are distributed (each user stores data in its own buffer

until the base-station allows it to transmit) and the base-station has no prior knowledge of user's buffer status.

Figure 3-9: Distributed data buffers in wireless networks

In this section we propose some solutions for the implementation of wireline scheduling schemes in wireless networks. As an example, we also discuss a scheduling scheme which can be used in wireless networks depending upon the service requirements. The work in [42] and [43] can be extended to find the upper bound on the end-to-end delay of an LMCS active connection, where the LMCS hub and the subsequent switches (in the connection path) employ the hierarchical scheduling.

3.2.2 Hierarchical-Fair-Queueing Scheduling

3.2.2.1 Link Sharing

Link Sharing is a technique of efficiently transferring the data of multiple users on the same communication channel (for detail review read [38]). In general, link sharing can be classified as;

- Flat Link Sharing, and
- Hierarchical Link Sharing

In flat link sharing all users who share the link (and who may or may not belong to different ATM service classes) are at the same level of service hierarchy. In hierarchical link sharing, a hierarchy of users (e.g., based on ATM service classes) is defined for link sharing. Since ATM is a class based service, it is expected that a scheduling scheme defined on class hierarchy would perform better for an ATM network (or any switching scheme based on service classes). The scheduling scheme determines the allocation of the shared channel bandwidth amongst users.

A few assumptions are given below for the comparison of flat and hierarchical link sharing.

- The switch is output buffered with service capacity of μ cells/sec.
- Since CBR (constant bit rate) traffic is easily dealt with separately, we consider only VBR and ABR traffic.

- The real-time VBR traffic is comprised of N_{VBR} connections with individual rate guarantees of ω_i cells/sec, usually representing the sustainable cell rate (SCR).
- The non-real-time traffic consists of N_{ABR} connections with individual rate guarantees of ψ_i cells/sec, representing the minimum cell rate (MCR).
- The following inequality must hold for stable queueing behavior at the output link;

$$\sum_{i=1}^{N_{VBR}} \omega_i + \sum_{i=1}^{N_{ABR}} \psi_i \leq \mu \quad (3.3)$$

- The ABR connections require a minimal bandwidth;

$$\Psi = \sum_{i=1}^{N_{ABR}} \psi_i \quad (3.4)$$

- The actual service rate extended to ABR traffic is $\Theta \geq \Psi$.

3.2.2.1.1 Flat Link Sharing

A single server provides service to all users (who may belong to different service classes) in an integrated services environment. Conceptually this is represented as a one-level (flat) service tree as shown in figure 3-10.

Each leaf node in the tree (figure 3-10) represents a queue and branch weight (e.g. ω_1) represents its rate allocation. To provide maximum delay guarantee separate queueing is required for each real-time user. Whereas a single queue is used for non-real-time (ABR) users. Since all queues in figure 1 get equal relative shares of the available bandwidths, the flat hierarchy may cause problems for delay sensitive traffic. More specifically, data traffic could receive large amounts of bandwidth while real-time connections are backlogged.

Figure 3-10: Flat Link Sharing

A better strategy is to serve ABR traffic at its guaranteed rate Θ cells / second, only allocating it extra bandwidth if no real-time connections are backlogged. This objective can be achieved using a hierarchical link sharing approach.

3.2.2.1.2 Hierarchical Link Sharing

Based on the real-time service class (CBR, rt-VBR) and non real-time service class (ABR, UBR) a two-level service hierarchical tree is shown in figure 3-11. At level 1, there are two servers, real-time server (VBR server) and non real-time server (ABR server) with individual link share of Λ cells/sec and Θ cells/sec respectively. The real-time connections (CBR / VBR services) are given a higher priority for the remaining available link capacity, namely $\Lambda = (\mu - \Theta)$ cells/sec. Hence the strategy favors real-time connections by regulating the ABR cell rate.

Figure 3-11: Hierarchical Link Sharing

3.2.2.2 Hierarchical Fair Queueing

The Hierarchical scheduling scheme proposed in [37] combines the idea of hierarchical link sharing with a modified version of self-clocked-fair-queueing (refer to [36], [39], [40])

and [41]). The proposed service model, hierarchical fair queueing, is shown in figure 3-12. This is a two-level hierarchy consisting of three servers: VBR (real-time) and ABR (non real-time) traffic servers at level 1, and the link server at level 2. The VBR-server and link server are of fair queueing type, whereas the ABR-server gives service priority to resource management (RM) cells in order to minimize feedback delays to source end-systems.

As shown in figure 3-12, each real-time connection (virtual connection VC^i) has a separate queue, whereas the non-real-time connections are aggregated into a single data cell buffer. In the proposed scheme only HOL (head-of-line) packets are time stamped to reduce the implementation complexity.

Two parameters are defined for each real-time connection VC^i , VBR-server and ABR-server, namely, its virtual time function $F(t)$ and head-of-line (HOL) stamp value $S(t)$. $F_{VC^i}^i(t)$, $F_{VBR}(t)$ and $F_{ABR}(t)$ represent the virtual time function of real-time connection i , VBR-server and ABR-server, respectively. The global virtual time function (virtual time of link server) indicates the time of the cell in service, whereas other virtual time functions indicate the service time each server's HOL packet. The head of line time defines the priority of service time of different servers (here we assume that cells are served in increasing head of line time stamp). $S_{VC^i}^i(t)$, $S_{VBR}(t)$ and $S_{ABR}(t)$ represent the HOL time of real-time connection i , VBR-server and ABR-server, respectively. In addition, there is a global virtual time stamp defined for the output link server, $v(t)$. This function represents the HOL stamp value of the current cell in service (or the last cell served if

the link is idle). At the start of each time slot, the HOL stamp values of the VBR-server and the ABR-server are compared. The server with minimum HOL stamp value is served with all ties going in favor of the VBR-server. If the HOL stamp of VBR-server is found to be a minimum, then the virtual connection with the lowest HOL stamp value is selected for service. The cell arrival and departure algorithm are explained in appendix 1.

Figure 3-12: Hierarchical Fair Queueing

3.2.2.2 Application in LMCS

Future broadband fixed wireless system (e.g., Local Multipoint Distribution systems, LMDS) will provide bidirectional broadband integrated services to residential/commercial subscribers at fixed location at 28Ghz as shown below.

Figure 3-13: Local Multipoint Distribution system (LMDS)

The Hierarchical fair queueing scheduling has been proposed for wireline systems where each subscriber has a dedicated link to the switch (e.g., ATM switch). The subscriber data queues are located at the switch as shown in figure 3-1. The subscribers share the link/links between switch/ switches. In such a scheme supplying the committed link share to each individual subscriber is relatively simple.

In wireless systems, the link between the subscribers and the base-station is shared among users. The base-station is responsible for scheduling the subscriber transmissions. In this case, the base-station has no prior knowledge of the subscribers buffer (located at subscriber's terminal). Depending on the service class, (declared at the time of connection setup) the scheduler at the base-station plans the transmission of users of different service classes as explained in the subsequent sections.

i) Constant Bit Rate Terminals

A CBR user requires the bandwidth at constant regular intervals. The request for such connection is conveyed to the base-station only once at connection set-up time. Dummy data buffers for CBR terminals are maintained at the base-station. A technique similar to the leaky bucket token generation is used to generate dummy cells at regular intervals for each CBR connection. These cells are stored in the dummy data buffer. Hence bandwidth is assigned to CBR terminals at regular intervals. The proposed scheme is shown in figure 3-14.

Figure 3-14: Conceptual diagram of Slot Allocation for real-time CBR Traffic

ii) Real-Time VBR Terminals

Traffic generated by the rt-VBR terminals varies with time and can afford only a limited transmission delay. For these connections scheduling for cells of successive cell burst can be done in two ways:

- Contention
- Polling

Figure 3-15: Conceptual diagram of slot allocation for real-time VBR traffic.

In contention mode, the terminals use contention slots to inform the base-station of the arrival of a new burst of cells. The delay involved in the contention process has stochastic bound and can be minimized by limiting the number of users who have access to them. Efficiency is improved using mini-contention slots (as in IEEE 802.14 MAC and MCNS MAC) and possibly by utilizing dynamic slot allocation schemes. After receiving a request from a rt-VBR connection the provisions of committed QoS is similar to the wire-line scheduling scheme

Polling of users at regular intervals equal to an average cell rate declared at connection set up is also appropriate for small (as explained in example 1) user population. In such a scheme the base-station maintains a dummy buffer for each rt-VBR connection. The status of the buffer is updated after each poll response from the user. The operation is shown in figure 3-15.

Example 1: Low user population

Suppose there are 8 active sources each generating on average 1.5 Mbps traffic. Also assume that the upstream link capacity is 15Mbps and the frame duration is 3 msec. The number of time slots in each upstream frame is

$$\text{No. of TS upstream frame} = \frac{15 \times 10^6}{68 \times 8} \times 3 \times 10^{-3} = 82.7 \approx 83 \text{ Time Slots} \quad (3.5)$$

The upstream frame consists of 8 poll response slots (1.45 Mbps), 4 contention slots (0.72 Mbps) and 71 reserve slots (12.83 Mbps). In this case all eight users can request additional upstream bandwidth either in poll-response slots or contention slots, which gives a maximum request delay of 3 msec.

Example 2: High user population

Assume the same upstream channel as described in example 1, with 200 active users having average data rate of 64Kbps. Also suppose that out of 83 time slots in the upstream frame, 6 time slots are used for contention (1.05 Mbps), 6 time slots are assigned for poll response (1.05 Mbps) and 71 time slots (12.9 Mbps) are employed for actual data transmission. If a fixed polling scheme is used then each user would be polled every 33rd frame. Contention slots may be used for initial and additional bandwidth request. If a collision occurs the user gets involved in a collision resolution process. If the hub polls a user engaged in the collision resolution process then the user will send its request in the poll response slot and will leave the collision resolution process. Hence the upper bound on request delay is approximately 100 msec which can be reduced with adaptive polling schemes.

If the request delay is required to be lower, than peak bandwidth allocation needs to be done for every user, resulting in waste of the link capacity. To implement adaptive polling schemes many factors are required to be considered for example, source delay sensitivity and source burstiness. It might be appropriate to poll the source with low average rate at their peak rates while the sources with moderate or high average rate to be polled at SCR.

iii) ABR - Terminals

ABR users can be of two types;

- Persistent users
- Non persistent users

The case of persistent ABR users (e.g., file transfer) is relatively simple. The base station allocates at least as many time slots (in each frame) to a persistent ABR user as were committed at the connection set-up time, (i.e., minimum cell rate). Additional time slots (in a frame) are assigned if not required by rt-VBR connections and/ or non-persistent ABR terminal.

In the case of a non-persistent ABR user the allocation of time slots in a frame is based on the information received in last resource management cell (RM) and available link capacity. Though further investigations are required, it is expected that a ABR flow control scheme (proposed for ATM networks such as [46], [47], [48]) would increase the utilization of the wireless link, since the load on contention slots would be reduced.

3.3 Slot Allocator

In case of contention-reservation mode of operation the upstream frame consists of a number of contention and reserve slots. For fixed slot allocation scheme, the number of contention slots and data slots are fixed in each frame. While in a dynamic slot allocation scheme, each frame may consist of both contention and data slots, or only contention slots, or only data slots.

The motivation for the use of dynamic slot allocation scheme (refer to [13], [14]) is that under low load conditions the LMCS-hub can provide more contention slots (because there are few requests for data slots) thereby reducing request delay. Whereas, under high load conditions, when a number of requests are already waiting for bandwidth, the hub provides only a minimum number of contention slots and a majority of reservation slots so as to minimize the queueing delay. The reason for this scheme is that when a number of requests are already pending, providing new contention slots means accepting new requests for bandwidth which is already scarce. This results (provision of new contention slots) in delaying pending requests while allowing new contentions and hence increasing queueing delays. The scheme in which the hub first clears the pending requests before opening new contention slot is termed as “data slot priority” scheme. We use different dynamic slot allocation schemes for the ternary tree and binary exponential backoff algorithms. This is because of the difference in their operation and the difference in the parameters known to the LMCS-hub for different CRAs. The Following parameters are used to describe the data cell priority algorithm.

N_R = No. of data cells required for pending request (value known to LMCS-hub)

C_p = No. of Contention slots required for pending collisions (value Known to LMCS hub in case of ternary tree CRA)

$C_N = C_S R_N$ = No. of Contention slots required for new arrivals (to be estimated by LMCS-hub)

N_S = Total number of slots per frame (value known to LMCS-hub)

$\widehat{R}$ = Average request size (depends on the supported applications)

C_S = Average number of contention slots required for one success (approximately 3)

$\widehat{A}$ = Arrival rate of new requests (estimated by LMCS-hub)

F = Time elapsed since last contention slots for new requests was opened (known to LMCS-hub in case of ternary tree CRA)

R_N = New requests in next frame, ($R_N = \widehat{A} F$),

D = Number of reserve slots in next frame.

C = Number of contention slots in next frame.

While using the ternary tree CRA, the LMCS-hub controls the collision resolution process. Among other parameters, the LMCS-hub has the exact knowledge of the pending collisions (to be resolved) and the time elapsed since the contention slots for new requests was provided. Based on this information we have used the algorithm (figure 3-16) which is basically a data slot priority scheme. In this approach the LMCS-hub creates only data slots in the coming frame when the number of data slots required is high. As soon as the requests waiting for data slots are cleared (or the required data slots are less than time slots per frame), the hub utilizes the remaining slots to resolve the pending collisions. The

excess slots (after clearing data slots requests and allocating slots to pending collisions) would be used for new requests. In p-tree (with $p=1$) CRA, the users with new requests select a contention slot from the available contention slots (in a frame) for new requests. Hence the number of contention slots in a frame for new requests affects the collision multiplicity (for example a single contention slot in a frame for new requests has high probability of collision). The following algorithm tries to assign a bulk of contention slots for new requests so as to keep the collision multiplicity at low level.

```

if ( $N_R \geq N_S$ )
    set  $D = N_R, C = 0$ 
else if ( $N_R + C_P \geq N_S$ )
    set  $D = N_R, C = N_S - N_R$ 
else if ( $N_R = 0$  and  $C_P = 0$ )
    set  $D = 0, C = N_S$ 
else if ( $C_P = 0$ )
    if ( $C_N > N_S - N_R$ )
        set  $D = 0, C = N_S$ 
    else
        set  $D = N_R, C = N_S - N_R$ 
else if ( $C_N > N_S - N_R - C_P$ )
    if ( $C_N > N_S - C_P$ )
        set  $C = C_P, D = N_R$ 
    else
        set  $C_N = N_S - C_P, C = C_N + C_P$ 
else
    set  $C_N = N_S - N_R - C_P, C = C_N + C_P, D = N_R$ 

```

Figure 3-16: Pseudo-code of Dynamic Slot Allocation Algorithm For Ternary Tree

On the other hand, the binary exponential CRA is distributed (the collided users take part in the collision resolution process) and both the collided users and the new users select the contention slot from the set of available contention slots based on the number of collisions the user has suffered. Contrary to the ternary tree CRA, the new users select the contention slots from their data-start window (or initial back-off window). Hence the number of contention slots in a frame has no effect on the collision multiplicity which is effected by how frequently the contention slots are provided. The pseudo-code for the dynamic slot allocation for the binary exponential CRA is given in figure 3-17.

```
if ( $N_R \geq N_S$ )
    set  $D = N_R \cdot C = 0$ 
else
    set  $D = N_R \cdot C = N_S - N_R$ 
```

Figure 3-17: Pseudo-code of Dynamic Slot Allocation Algorithm for Binary Exponential

Although in our simulations we do not vary the probability of transmission for new requests, it can be used as a mean to control the collision multiplicity (refer to [26], [27], [29]). For example, if C_{AN} is the number of available contention slots for new requests in the coming frame, then the probability of transmission, P_T , can be calculated as follows

$$P_T = \begin{cases} 1 & \text{if } (C_{AN} \geq C_N) \\ \frac{C_{AN}}{C_N} & \text{if } (C_{AN} < C_N) \end{cases} \quad (3.6)$$

Chapter 4

Candidate Multiple Access Protocols

The high cost and resource scarcity of broadband access networks (for example broadband wireless networks) demand their efficient utilization. This can be achieved by sharing the access link among many users through the use of multiple access schemes. Frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA) are three widely used access techniques used to share the available bandwidth. In FDMA systems resources are wasted during the source idle periods. TDMA schemes seems more appropriate than the FDMA schemes since bandwidth can be assigned on demand by changing the number of assigned time slots. Although it may be argued that CDMA systems provide significant capacity gains, this scheme is at least presently not considered because systems operating with data rates in the 10's of Mbps range would require very high chip rate. This high chip rate appears presently difficult to attain because of hardware implementation complexity.

Hence TDMA schemes seems to be the most appropriate choice. Traditional TDMA based multiple access schemes such as ALOHA, CSMA and PRMA are not suitable because of low utilization, instability, absence of QoS guarantees and presence of wide range bit rate sources. In this chapter we will study few well known TDMA based MAC protocols pro-

posed by various broadband access technology groups which include the DAVIC, IEEE 802.14 working group and MCNS/ SCTE.

4.1 DAVIC 1.2 MAC Recommendations

DAVIC (Digital Audio Visual Council) is a non-profit organization with the goals to define the specifications for interfaces, protocols and architecture of digital audio-visual applications and services.

The DAVIC 1.0, DAVIC 1.1 and DAVIC 1.2 specifications were developed by the participating DAVIC members in response to the Calls For Proposals to members and non-members. The specifications for the LMCS/ LMDS systems are given in part 8 (Lower Layer Protocols and Physical Interfaces) of the DAVIC 1.2 recommendations. A detailed description of the DAVIC 1.2 MAC recommendations for LMCS can be found in that section (for details refer [50]).

4.1.1 MAC Highlights:

Few major characteristics of the MAC include:

- Bandwidth is assigned on demand by the LMDS-hub called the AIU (Air Interface Unit).
- ATM and MPEG-2 transport modes are supported.
- A fixed Frame duration of 3 to 6 milli-seconds is defined for both downstream and upstream channels.

- A downstream channel consists of two types of time slots: Frame Start Time Slot (for control message) and Random Access Time Slots (for data transfer to individual users).
- Upstream frame consists of three types of time slots: Polling Response time slots, Contention time slots (for bandwidth request and short data transfer) and Reserved time slots (for data transfer).
- Contention and Polling are used for upstream bandwidth requests.
- The choice of collision resolution algorithm and the data cell scheduling are left for the vendor.

4.1.2 MAC Message Formats

In this section we provide an overview of the upstream and downstream message structures.

4.1.2.1 Generic MAC Message Format

Both upstream and downstream use a similar message structure [figure 4-1], with possibly different size of the time slot. When carrying MAC messages the time slots contains physical media dependent overhead (PMD), MAC header and MAC messages. In case of data transfer the time slots consist of PMD and data PDU.

FIGURE 4-1 : Generic MAC Message Format for DAVIC

4.1.2.2 MAC Header Format

The MAC header format and its description are given in figure 4-2 and table 4-1 respectively.

FIGURE 4-2 : MAC Message Structure for DAVIC

S.No.	Field	Name of the Field	Size	Description
1	NI	NTU_Identifier	2 bytes	Unique identifier of a specific NTU.
2	ML	Message_Length (ML)	2 bytes	Indicates the number of bytes following the message length in this message. The cell contains more than one message which may be meant for single or multiple NTU.
3	PSID	Poll Slot Identifier	1 byte	Designates poll response slot. A downstream zero value indicates that the NTU is not being polled by this message.
4	MT	Message Type	1 byte	Any DAVIC Message. e.g. reservation_request, reserved_slot_allocation, etc.
5	NMI	No. of Message Items	1 byte	Number of items of the designated message type.
6	MI	Message Item	N bytes	List of items of the designated message type.

Table 4-1: MAC Header Description for DAVIC

4.1.2.3 Upstream Slot Structure:

The upstream frame consists of time slots [figure 4.3], which contain 4 bytes of preamble, 1 byte of guard band, 53 bytes of ATM cell and 10 bytes of FEC (Forward Error Correction).

FIGURE 4-3 : Upstream Time Slot Structure for DAVIC

4.1.2.4 Downstream Time Slot Structure

The downstream frame uses two types of time slot structures: ATM and MPEG2.

4.1.2.4.1 Time Slot Structure for MPEG2 Transport Stream

In case of MPEG2 TS the frame consists of time slots of 204 bytes which contain 1 byte of synchronization, 187 bytes of data PDU and 16 bytes of FEC [figure 4-4].

FIGURE 4-4 : Framing Structure when carrying MPEG2-TS for DAVIC

4.1.2.4.2 Framing Structure for ATM Transport Stream

The downstream framing structure when carrying ATM cells is shown in figure4-5.

FIGURE 4-5 : Framing structure when carrying ATM for DAVIC

4.1.3. Time Slot Types

4.1.3.1 Downstream Time Slots

There are two types of time slots in the downstream frame.

I. Frame Start Time Slot [FS]:

- Each frame begins with Frame Start Time Slot. It beacons the start of a new frame & helps NIU (Network Interface Unit) to synchronize its Upstream Frame.
- It contains Frame Number and DAVIC MAC management messages for example, sign_on_request, contention_slot_feedback, etc.

II. Random Access Time Slots [NIU]:

- All time slots except first time slot are Random Access Time slots.
- AIU (Air Interface Unit) utilizes these slots to transmit cells to a single NIU (Network Interface Unit).
- Assigned by the Slot Assignment Manager without the probability of collision.

FIGURE 4-6 : A possible scenario of downstream Frame Structure for DAVIC

4.1.3.2 Upstream Time Slots

There are three types of time slots used in upstream.

I. Polling Response Time Slots[P]:

- NIU responds to the poll_request from AIU.
- Its payload contains DAVIC MAC messages, e.g., status_reponse message.

II. Contention Time Slots[C]:

- Contention slots may be allocated to all NIU's or a group of NIU's.
- Carries Bandwidth_Request or short information messages, e.g., video games application.

III. Reserved Time Slots[R]:

- One or multiple slots may be allocated to an NIU by Slot Assignment Manager.
- The location and number of Contention and Reserved TS in a frame is adaptive.

4.1.4 MAC Management Messages

The purpose of the MAC protocols is to control the activity of the stations on the shared channel with the help of MAC management messages. A detailed messaging is required between the NIU (network interface unit) and AIU (air interface unit) which ranges from network entry to the transmission of actual information. The complete list of DAVIC MAC messages and a their description is given in table 4-2.

S.No.	MAC_message_type	Slot Type	Delivery	Description
1	reservation_request	[C]	AIU $\leftarrow$ NIU/STB	NIU request for reserved time slots
2	reserved_slot_allocation	[FS,NIU]	AIU $\rightarrow$ NIU/STB	Allocation/deallocation of reserved time slots.
3	contention_slot_allocation	[FS,NIU]	AIU $\rightarrow$ NIU/STB	Allocation/deallocation of contention time slots.
4	poll_slot_allocation	[FS,NIU]	AIU $\rightarrow$ NIU/STB	Allocation/deallocation of poll time slots.
5	sign_on_request	[FS]	AIU $\rightarrow$ NIU/STB	Parameter for an NIU to enter the network.
6	tx_calibration	[FS,NIU]	AIU $\rightarrow$ NIU/STB	NIU transmit freq. power, time corrections.
7	status_request	[FS,NIU]	AIU $\rightarrow$ NIU/STB	Request specified NIU status items.
8	status_response	[P]	AIU $\leftarrow$ NIU/STB	Requested NIU status items.
9	mac_session_request	[C]	AIU $\leftarrow$ NIU/STB	NIU request a session/control connection
10	mac_session_connection	[FS,NIU]	AIU $\rightarrow$ NIU/STB	AIU assigns VPI/VCI for session connection
11	mac_session_release	[FS,NIU]	AIU $\leftrightarrow$ NIU/STB	AIU release a session connection.
12	mac_session_msg_ack	[FS,NIU, C,P]	AIU $\leftrightarrow$ NIU/STB	Acknowledgment of receipt of the 3 above messages.
13	new_downstream_channel	[FS,NIU]	AIU $\rightarrow$ NIU/STB	Command NIU to enter net on new channel
14	contention_slot_feedback	[FS]	AIU $\rightarrow$ NIU/STB	Contention slot stabilization feedback.

Table 4-2: DAVIC MAC Messages

4.1.5 NETWORK ENTRY PROCEDURE

- Step-1:** NIU may be polled on more than one downstream frequency channels before it enters the network.
- Step-2:** When an NIU attempts to enter the network, it acquires a downstream frequency channel and listens for the poll directed to it.
- Step-3:** AIU sends the partial or full serial number along with NIU_ID in the poll_request message.
- Step-4:** One NIU may be polled twice before another NIU is polled, hence polling scheme may not necessarily be Round Robin.
- Step-5:** Each NIU is polled at least every 2 seconds in worst case. Therefore, if an NIU does not receive the poll message in 2 seconds then it would switch to the next frequency channel. This process repeats unless the NIU finds the channel on which it is being polled.
- Step-6:** Before allocating contention and reserved time slots the NIU is calibrated i.e., transmit_signal calibration,time_alignment, etc.

FIGURE 4-7 : Network Entry Procedure for DAVIC

4.1.6 Protocol Example

Once an NTU has entered the network, it may use either contention slots or the poll-response slots to request for the upstream bandwidth. The acknowledgment of the contentions for bandwidth is sent in the next downstream frame. If the NTU uses contention slot for the bandwidth request then its request may collide with other NTUs' requesting bandwidth in the same contention slot. As a result a contention resolution process is initiated and any suitable collision resolution algorithm (CRA) may be employed, DAVIC does not limit the choice of CRA. After the request has been received by the AIU either the bandwidth is allocated or the request is queued. If additional bandwidth is required then the NTU uses either poll-response slots or a contention slot.

4.2 IEEE 802.14 MAC Proposals

The IEEE 802.14 MAC proposals are prepared by the IEEE 802.14 working group committee which include members from Lucent, AT&T, NIST, etc. The goal is to define a standard for data transfer over hybrid fiber/coax networks between the customer (called Station) and the head-end. A summary of the proposals is given below and the more detailed discussion can be found in section 4 of the [51] and [52].

4.2.1 MAC Highlights

The following are few key characteristics of IEEE802.14 MAC.

- The head-end controller (HC) allocates bandwidth on demand to the requested stations.
- ATM, MPEG-2 and variable length fragment transport modes are supported.
- No frame structure for upstream and downstream is specified.
- Upstream channel consists of contention mini-slots and reservation minislots.
- Contention is used for initial bandwidth request and piggybacking is employed for additional bandwidth requirements.
- Ternary tree collision resolution algorithm is used to resolve collisions.
- The choice of data cell scheduling is left for the vendors.

4.2.2 Upstream Channel Hierarchy

The Upstream channel is divided into a sea of min-slots. The duration of a mini-slot is the time required to transmit 8 bytes of data, the time required to transmit physical overhead and guard time [figure 4-8].

FIGURE 4-8 : Mini-Slot structure for IEEE 802.14

4.2.3 Downstream Channel hierarchy

The downstream channel consists of a stream of 6 bytes allocation units which can be concatenated to carry ATM cells or variable length fragments [figure 4-9].

FIGURE 4-9 : Downstream Channel Hierarchy IEEE 802.14

4.2.4 Types of Upstream Mini-slots

The upstream channel contains two types of mini-slots

1. Contention mini-slots
2. Reservation mini-slots

Contention mini-slots are used by the stations to request for upstream bandwidth. The reservation mini-slots are used to transfer actual information. Multiple reserve mini-slots are combined to send ATM cells or variable length PDU.

4.2.5 Bandwidth request procedure

The stations may use the following two methods to request for the upstream bandwidth.

1. Contention
2. Piggybacking

Contention procedure is employed by the stations for the initial bandwidth request and piggybacking is used for the additional bandwidth requirements.

4.2.6 Information Elements Type

Information elements contain specific control messages for the network management as described in table 4-3. The upstream and downstream MAC management messages may contain a number of information elements.

Type	Direction	Usage
Assign Parameters	Downstream	Registration
Assign Parameters Acknowledge	Upstream	Registration
Connect	Downstream	Registration
MKE Indication	Downstream	Security
MKE Response	Upstream	Security
QKE Indication	Downstream	Security
QKE Response	Upstream	Security
Multicast Key Indication	Downstream	Security
Multicast Key response	Upstream	Security
Downstream frequency Change	Downstream	Management
MAC local Identifier Add	Downstream	Management
MAC Local Identifier Delete	Downstream	Management
Multicast Local Identifier Add	Downstream	Management
Multicast Local Identifier Delete	Downstream	Management
ATM Slot grant	Downstream	Bandwidth
Request Minislot Allocation Element	Downstream	Bandwidth
Request Minislot Contention Feedback	Downstream	Bandwidth
Extended Bandwidth Request Feedback		Bandwidth
Request PDU feedback	Downstream	Bandwidth
Error	Both	Diagnostic

Table 4-3: Types of Information Elements in IEEE 802.14

4.2.7 Protocol Example

It is an HFC-specific MAC protocol and uses TDM downstream and TDMA upstream. The smallest unit of upstream bandwidth allocation is a mini-slot which consists of 8 bytes (of data). A number of minislots can be added to transmit ATM cell or variable length packets. The upstream channel consists of contention mini-slots (CMS) and reserve mini-slots. To transmit ATM cells or variable length messages a number of reserve mini-slots are concatenated.

After the connection is made (ranging and registration) if the user has data to transmit, it waits for the CMS for new users. In case of blocked access n-ary tree algorithm, new users are not allowed to transmit their requests unless all pending collisions have been resolved. When a CMS for new users is found then the user transmits its request. In case of collision the user gets involved in a collision resolution process. Finally the request reaches the head-end controller which assigns bandwidth when it is available. The user may request additional bandwidth using piggybacking, i.e., the extra bandwidth may be requested in data slots EBR (extended bandwidth request) field.

4.3 MCNS MAC Standard/ DOCSIS

The Data Over Cable Specifications (DOCSIS) documents describe the internal and external network interfaces for a cable system that allows bi-directional transfer of IP traffic (possibly ATM and other PDU formats in future versions), between the head-end and the customer over the hybrid fiber/coax network.

This project was initiated by an organization named Multimedia Cable Network System (MCNS) whose participants are Comcast Cable Communications, Time Warner Cable, Cox Communications and Tele-Communications Inc. In addition to MCNS, Rogers Cable Systems Limited, Media One and CableLabs also contributed to the DOCSIS documents.

In the following section we briefly discuss the MAC defined in DOCSIS documents (for details refer [53]).

4.3.1 MAC Highlights

Some of the key protocol characteristics are as follows:

- Bandwidth is assigned on demand by the base-station which is termed the Cable Modem Termination Systems (CMTS).
- Upstream and downstream channel consists of a stream of mini-slots. The size of a minislot varies depending on the modulation scheme and channel rate.
- No frame structure is specified for the upstream and the downstream channels.
- The Upstream channel contain two types of mini-slots; Contention mini-slots

and Data mini-slots.

- A cable modem (CM), a LMCS-user, uses contention procedure for initial bandwidth requests and piggybacking for additional bandwidth requirements.
- Support of Elastic and Inelastic class of service.

4.3.2 Mini-Slots and Frame

A mini-slot is the smallest unit of upstream transmissions. The duration of the mini-slot is given by the following relation

$$\text{Mini-Slot Duration} = 6.25 \times 2^M \text{ } \mu\text{secs.}$$

where $M = 1, 2, 3, \dots, 7$

The number of bytes in a mini-slot depends on the modulation scheme and the channel rate. The minimum size of the mini-slot should be 32 symbols. For example, for uplink capacity of 5Mbps using QPSK (2 bits/symbol efficiency) the minimum slot size is 8 bytes and in 16-QAM which gives 4 bits/symbol efficiency we get a 16 byte mini-slot. Both upstream and downstream consists of a stream of minislots.

The unit of data exchange between MAC sub-layer at the CMTS and a given CM in MCNS is called a frame. A frame consists of a number of mini-slots which carries a MAC Header and ATM cells or a variable length data PDU. The same frame structure is used in upstream and downstream. MAC frames are variable in length.

4.3.3 MAC Frame Formats

In this section a general structure used in the upstream and downstream channels is explained.

4.3.3.1 Generic MAC Frame Format

The generic structure of the upstream and downstream messages is given in figure 4-10.

FIGURE 4-10 : Generic MAC Message Format For MCNS

4.3.3.2 MAC Header Format

All MAC management messages and data PDU carry the MAC header [figure 4-11]. The size of this header is 6 bytes when the extended header (EHDR) field is not used. The size of the extended header field varies with its use (which depends on its combination with other field in the MAC header) for example it carries 4 bytes of overhead when used for piggybacking (i.e., additional bandwidth request).

FIGURE 4-11 : MAC Header Format For MCNS

S.No.	MAC Header Filed	Size	Description
1	FC	1 byte	Frame Control, Identifies type of the MAC Header
		FC_TYPE 2 bits	00, MAC Header with Packet PDU 01, Header with ATM Cell 10, Header with Reserved PDU 11, MAC Header for specific MAC control purposes
		FC_PARM 5 bits	00000 for Packet, ATM, Reserved PDU's and Timing MAC specific Header 00001, MAC Management Head 00100, MAC Header for mini-slots Request 00101 MAC Header for ATM Cell request
		EHDR_ON 1 bit	0 = Extended Header not used 1 = Extended Header used. Not used in Timing, Request, concatenation MAC Headers
2	MAC_PARM	1 byte	Parameter field whose use is dependent on FC. if EDHR_ON = 1; used for EHDR field length (ELEN) else if for concatenated frames used for MAC frame count else for Requests only, indicates the number of mini-slots and/ or ATM cells requested.
3	LEN (SID)	2 bytes	The length of the MAC frame. Its the sum of the number of bytes in the extended header (if present) and the number of bytes following HCS. In case of Request MAC Header it indicates the Service ID (SID) of the requested user.
4	EHDR	0-240 bytes	Extended MAC Header (where present; variable size)
5	HCS	2 bytes	MAC Header Check Sequence

Table 4-4: MAC Header Description For MCNS

4.3.3.3 MAC Management Message Header and Messages

Figure 4.12 shows the MAC Management Message format which includes MAC Header, MAC Management Message Header, Management Message Payload and CRC.

FIGURE 4-12 : MAC Header and MAC Management Message Header Fields For MCNS

S.NO.	Field	Length	Description
MAC Header			
1	FC	1 byte	Frame Control (explained in table 4-4)
2	MAC_PARM	1 byte	MAC Parameters (explained in table 4-4)
3	LEN	2 bytes	Length (explained in table 4-4)
4	HCS	2 bytes	Header Check Sequence
MAC Management Message Header			
5	DA	6 bytes	Destination Address
6	SA	6 bytes	Source Address
7	Msg LEN	2 bytes	MAC message length from DSAP to the end of the payload
8	DSAP	1 byte	The LLC null SAP(00)
9	SSAP	1 byte	The LLC null SAP(00)
10	Control	1 byte	Unnumbered information frame (03) as defined[ISO8802-2]
11	Version	1 byte	Indicates the version of the MAC management protocol in use (1 for current version).
12	Type	1 byte	States the type of MAC management message follows (described in table xx)
13	RSVD	1 byte	Used to align the message payload on a 32 bits boundary (0 for this version)
14	Management Message Payload	Variable length	MAC messages described in table 4-6
Error control Header			
15	CRC	Variable length	Cyclic redundancy check. Covers the MAC management message and management message protocol.

Table 4-5: MAC Management Message Description For MCNS

Type Value	Message Name	Message Description
1	SYNC	Time Synchronization
2	UCD	Upstream Channel Descriptor
3	MAP	Upstream Bandwidth Allocation
4	RNG-REQ	Ranging Request
5	RNG-RSP	Ranging Response
6	REG-REQ	Registration Request
7	REG-RSP	Registration Response
8	UCC-REQ	Upstream Channel Change Request
9	UCC-RSP	Upstream Channel change Response
10	TRI-TCD	Telephony Channel Descriptor[MCNS6]
11	TRI-TSI	Termination System information[MCNS6]
12	BPKM-REQ	Privacy Key Management Request[MCNS8]
13	BPKM-RSP	Privacy Key Management Response[MCNS8]
14-255		Reserved for future use

Table 4-6: Types of MAC Management Messages For MCNS

4.3.4 Types of Upstream Mini-slots

The upstream channel contains two types of mini-slots

1. Contention mini-slots
2. Reservation mini-slots

Contention mini-slots are used by the stations to request upstream bandwidth. The reservation mini-slots are used to transfer actual information. In ATM transport mode multiple reservation mini-slots are combined to form an ATM cell and in variable length fragment schemes reservation minislots are concatenated for variable size packets.

4.3.5 Bandwidth request procedure

The stations may use the following two methods to request upstream bandwidth.

1. Contention
2. Piggybacking
3. Polling/probing.

The contention procedure is employed by the stations for the initial bandwidth request and piggybacking/polling is used for the additional bandwidth requirements.

4.3.6 Protocol Example

After completing the initial network entry procedure the user may use the contention mini-slots for an initial bandwidth request. The bandwidth may be requested for a number of reserved mini-slots or a number of ATM cells. A maximum of 256 ATM cells or mini-slots may be requested. In case of collision of request, the cable modems (CM) use a truncated binary exponential back off algorithm to resolve collisions. After the request is received by the CMTS the bandwidth is either assigned or the requests are stored. Only one outstanding request per service ID (SID) is allowed. Piggybacking may be used for additional bandwidth request.

4.3.7 Collision Resolution Algorithm

MCNS uses truncated binary exponential backoff algorithm for resolving collisions. To regulate the traffic load on the request slots, the protocol defines two entry windows: initial and final data backoff windows. Depending on the traffic conditions the size of the two

windows may vary from 1 to 1024. In this way the performance and the stability of the CRA is improved.

A CM which has made initial ranging and registration, waits for the MAP (downstream MAC management message) message from the CMTS to request for bandwidth. The CM selects the request slot from the initial data backoff window and defers its request transmission until it finds the selected request slot. After sending its request the CM waits for the feedback message from the CMTS. In case of positive acknowledgment from the CMTS the CM waits for the data grant. If no acknowledgment is received or collision feedback message, the CM increments its initial data backoff window by a factor of two until it reaches the final data backoff window. The CM then again selects a request slot from its backoff window and retransmits in the chosen slot until a success occurs or the maximum number of retries has been reached. In the later case the PDU must be discarded. During the contention process, if a request slot is assigned only for it, then the CM uses that slot and leaves the contention process.

4.3.8 Classes of Service

The protocol divides the applications in two broader classes:

1. Elastic Applications
2. Inelastic Applications

Elastic Applications:

The applications which can afford some delay are termed elastic applications. The CM belonging to these applications contended for bandwidth and the CMTS serves such users as non-priority users. These applications may further be divided into two categories: interactive burst and interactive bulk. The interactive burst applications usually face lower delays than the interactive bulk applications.

Inelastic Applications:

These applications are more sensitive to delay than the elastic applications and the packets must reach their destinations within a reasonable time in order to be useful. Such services are further classified into: Delay-intolerant and Delay tolerant. The delay-intolerant services require tight upper bounds on delay which is not the case with delay-intolerant traffic. For delay-intolerant applications a fixed number of mini-slots is assigned at regular intervals. The CMTS assigns dedicated request slots to delay-tolerant users and then additional bandwidth is assigned based on the committed delay variation, bandwidth rate, and other considerations (for example, link bandwidth availability).

4.4 Comparison of the Candidate Protocols

The following section highlights the key differences among the three candidate MAC protocols (similar discussion can be found in [17]).

4.4.1 Some major similarities between the candidate protocols:

All three protocols are capable of active users physical parameters calibration (Power, Range, Frequency control etc.) and can assign users to frequency channels dynamically

(for load balancing). Each protocol uses encryption (and decryption) of individual data flows to ensure privacy in the broadcast environment. All three protocols employ a request/grant procedure for bandwidth allocation. Another common characteristic is the provision of demand assignment bandwidth allocation and the use of random access for registration and bandwidth request. For traffic regulation and priority management each MAC protocol can assign a subset of contention slots to a group of users. When operated in the ATM mode, each protocol can support effectively all ATM service classes with the capability of temporary and permanent bandwidth allocation (MCNS also intends to support IP service classes). All three protocols allow use of contention slots for short information transfer and support an MPEG-2 transport mode in the downlink direction.

4.4.2 Some major differences between the candidate protocols:

Some major differences between the candidate protocols are: For contention purposes both the IEEE 802.14 draft and MCNS use mini slots; a mini slot though in IEEE 802.14 MAC is defined as slot size large enough to transmit 8 bytes of information and overhead, whereas in MCNS a mini-slot is defined as a power-of-two (2^M , $M=0-7$) multiple of 6.25 μs , a nominal value could be 16 bytes ($M=0$, QPSK with symbol rate of 2.56 M symbols/s). DAVIC uses contention slot with size of one ATM cell (53 bytes and 15 bytes of overhead). Besides using contention to request bandwidth initially, piggybacking can be used for additional bandwidth request in 802.14 and MCNS while polling is an additional option in DAVIC and MCNS. IEEE 802.14 (and MCNS) do not impose any frame struc-

ture whereas a 3 to 6 msec frame structure (with a frame shared among multiple users) is recommended in DAVIC.

In terms of signalling, both the IEEE 802.14 and DAVIC protocol use ATM cells (802.2 LLC encapsulated in AAL5 frame - ITU-T I.363.5 recommendation). MCNS instead uses variable length MAC messages (802.2 LLC frames). Various MAC messaging and calculation of MAC header are entirely different in each of the protocols. Both IEEE 802.14 and MCNS can transport variable length packets and ATM cells whereas the slot granularity in DAVIC is that of an ATM cell.

IEEE 802.14 specifies “a ternary tree Contention Resolution Algorithm” (CRA), MCNS specifies a truncated binary exponential back-off CRA (low cost Ethernet type) for the resolution of collisions in the random access slots, whereas DAVIC does not specify the use of a particular CRA. Finally IEEE 802.14 and DAVIC protocols employ a ternary feedback mechanism(i.e. collision, no-collision and idle), while the MCNS protocol employs binary feedback.

Chapter 5

Traffic Models

Traffic models are used for capacity planning and performance evaluation of telecommunication networks. In this chapter we have described the traffic models used for the performance evaluation of the candidate MAC protocols for LMCS network.

The following factors were considered for the selection of the traffic models:

1. Since LMCS will support broadband integrated services, therefore, the performance of the MAC protocol needs to be examined under diverse and heterogeneous traffic conditions.
2. The main purpose of this thesis is to compare the performance of the DAVIC MAC protocol with the MCNS MAC and the IEEE 802.14 MAC proposals, as such the source model should also highlight the performance differences of the three candidate protocols (IEEE 802.14, MCNS and DAVIC)

Considering these factors we selected the following four traffic models:

- WWW Traffic Model
- Short-Bursty Traffic Model
- Batch-Poisson Traffic Model
- CBR Traffic Model

5.1 WWW Traffic Model

The growing popularity of the Internet applications makes it imperative on LMCS network operators to also support Internet traffic along with other service support. This demands that the selected MAC protocol should be able to support efficiently the internet connections. For this reason we selected the WWW traffic model given in [54], which is based on the real data measurements in GTE labs. The description of this model can also be found in [17].

The paper by Shuang Deng ([54]) describes the data traffic characteristics of individual subscribers on the future network based on today's WWW traffic. When a user requests a page, several URL requests may follow. The first one transmits the user's direct request to the server. The other requests may be automatically generated by the browser program, e.g., each in-line image (e.g., logos, icons, buttons, etc.) requires a separate request be sent automatically by the client program during the download of a page.

This behavior may be modeled by an ON-OFF process rather than the simple Poisson process. The active, or ON, period consists of series of requests which follows the inactive, or OFF, period. The wide data collection in a real environment (GTE Labs) supports the validity of the above model.

The complete description of this model is as follows.

5.1.2. TRAFFIC MODEL

Based on the work in [54], the source model can be described by the distributions of three random variables:

- 1) x : the duration of an ON period in seconds.
- 2) y : the duration of an OFF period in seconds.
- 3) z : the inter-arrival time of requests during an ON period in seconds.

The following section describes briefly the results in [54], which we used to build the WWW traffic model.

5.1.2.1 ON Period Distribution (in seconds)

- The exact boundaries of an ON and OFF periods are dependent on the definition of the minimum OFF period.
- A sequence of document requests with inter-arrival time less than 60 seconds are considered to form an ON period, and the occurrence of a request more than 60 seconds after the previous request indicates an OFF period. Two consecutive

OFF periods separated by a single request are combined into one. It was observed that the distribution is insensitive to the particular choice of the OFF period threshold.

- The actual data collected appears to belong to the Weibull distribution, whose probability density function is as follows.

$$p(x) = \frac{k}{\theta} \left(\frac{x}{\theta}\right)^{k-1} e^{-\left(\frac{x}{\theta}\right)^k} \quad (5-1)$$

- The probability distribution function of Weibull distribution is as follows.

$$F(x) = P(t \leq x) = 1 - e^{-\left(\frac{x}{\theta}\right)^k} \quad (5-2)$$

- The values of θ and k in [54] are as follows.

$$\theta = \exp(4.5)$$

$$\text{and } k = 0.88$$

where x is in seconds.

5.1.2.2 OFF Period Distribution (in seconds)

- It represents the thinking time of the user, which results in a significant pause in the communication activities.
- Requests with inter-arrival time interval longer than 6000 seconds can be considered as two separate sessions.
- The empirical results suggest that the duration of the OFF period belongs to Pareto distribution having the following probability density function:

$$p(y) = \alpha \cdot \frac{k^\alpha}{y^{\alpha+1}} \quad (5-3)$$

- The probability distribution function of a Pareto distribution is as follows.

$$F(y) = P(t \leq y) = 1 - \left(\frac{k}{y}\right)^\alpha \quad (5-4)$$

- The values of k and alpha for WWW types of traffic in [54] are as follows.

$$k = 60$$

$$\alpha = 0.5$$

where y is in seconds.

5.1.2.3 Inter-arrival Distribution During ON period (second)

- The empirical results show that the inter-arrival time distribution, $F(z)$, is given by (5-2). However, the values of k and θ are different from those that were used in the calculation of the ON period. These values are as follows:

$$k = 0.5$$

$$\theta = \exp(1.5)$$

A sample of requests generated by the WWW traffic model is shown in figure 5-1.

Figure 5-1 : A Sample of the WWW traffic pattern.

5.2 Short Bursty Traffic Model

It is used to model the delay sensitive sources which generate the short bursty messages for example video-games applications. The reason for the selection of this model is that the contention slot in DAVIC can carry a 48 byte message which is not possible in IEEE 802.14 simply because of smaller contention slots (8 bytes). This model helps us to highlight this factor in terms of mean-access delay and throughput.

This traffic type was proposed for the initial performance evaluation of the IEEE 802.14 MAC proposals ([55]). The message length is 48 bytes (and hence requires one ATM cell for its transmission). Active sources generate this traffic according to a Poisson distribution with varying mean arrival rate.

5.3 Batch Poisson Traffic Model

This model is used to represent sources with large request sizes. Such applications have low contention load and as a result require fewer contention slots. This is considered to be an interesting scenario to compare the two protocols because for the same number of data slots in a frame the two protocols can carry different amount of contention load.

Figure 5-2 shows the packet length distribution of Batch-Poisson traffic model with batch size corresponding to observed Ethernet PDUs [55]. This model was proposed by the IEEE 802.14 WG for the performance evaluation of MAC proposals ([55]). Each source generates packets of 369 bytes average length with mean arrival rate of λ packets per second.

Figure 5-2 : Message size distribution of Batch Poisson traffic

5.4 CBR Traffic Model

This traffic model is used to emulate voice traffic. The call arrival process is Poisson distributed with mean rate of λ calls per second. The call duration is exponentially distributed with mean duration of μ seconds. If the circuits are available and the call is accepted then the source generates traffic of 64 kbps or one ATM cell every 6 milli seconds for the duration of the call.

The traffic load is varied by either changing the mean call arrival rate λ or by varying the mean call duration μ .

Chapter 6

Simulation Models and Results Discussion

6.1 Simulation Studies

Two separate simulators for the DAVIC 1.2 MAC recommendations and DOCSIS MAC Standard were built in C++ to examine their performance (a brief description of simulator is given in Appendix 2). These simulators are generic and can be used for:

- Different Traffic Models.
- Variable user population and load conditions.
- A number of data cell scheduling scheme to analyze their suitability with the MAC.
- Any dynamic slot allocation (of CMS and data cells) scheme.
- Variable upstream frame size.
- Collecting performance metrics of interest.

The confidence interval test was made only for the Batch-Poisson traffic for the two protocols. For a confidence interval of 95% we were required to run on average 15 simulation runs for each statistics.

6.1.1 Confidence Intervals

The following procedure was used to calculate the confidence intervals.

The choice of initial conditions is critical for the estimation of confidence intervals. To reduce the impact of initial conditions we divided the simulation run into two phases:

1. Initialization Phase from time 0 to T_i .
2. Data Collection phase from time T_i to T_e .

The choice of T_i should be such that it is more representative of steady state behavior of the system than the original initial condition at time 0. To calculate the value of T_i , we run simulation for each load and took the run time average of mean access delay, $\bar{D}$. T_i is selected on the basis when $\bar{D}$ range reaches to steady state (varies within 5% range). Also length of T_e is chosen to be long enough so that it guarantees almost precise estimates of the steady-state behavior.

We run ' n ' statistically independent simulations at each load and calculate Mean Access Delay for each run ($D_1, D_2, \dots, D_n$) using a different seed. The point estimator of mean access delay is calculated as follows:

$$\bar{D} = \frac{1}{n} \sum_{i=1}^n D_i \quad (1)$$

$\bar{D}$ is the sample mean based on sample of size n . The sample variance V is given by

$$V = \sum_{i=1}^n \frac{(D_i - \bar{D})^2}{n-1} \quad (2)$$

The standard error, E , is the measure of the precision of a point estimator and is given by

$$E = \frac{V}{\sqrt{n}} \quad (3)$$

The approximate $100(1 - \alpha) \%$ confidence interval for $\bar{D}$ is then calculated using student t -distribution.

$$\bar{D} \pm t_{\frac{\alpha}{2}, f}(E) \quad (4)$$

where, f is the degree of freedom.

6.1.2 DAVIC Simulator and results discussion

Simulations were done to find the performance of the DAVIC MAC protocol ([50]) under homogenous and heterogeneous traffic conditions. The performance is measured in terms of mean-access delay, throughput, collision-multiplicity statistics, probability distribution function of mean-access delay, coefficient of delay-variation and call-blocking-probability (for CBR traffic). Although most of the scenarios deal with error free environments, the effect of channel errors has also been included in a few scenarios. In case of heterogeneous traffic models the effect on performance using hierarchical-fair-queueing scheduling has also been discussed.

6.1.2.1 DAVIC Simulation Model

Following are the general assumptions which are applicable to all scenarios of DAVIC MAC simulations discussed under the sections of homogenous and heterogeneous traffic. The assumptions specific to a particular scenario are mentioned under that section.

The upstream channel is divided into fixed length TDMA frames of 3.264 msec (for scenarios using Ternary Tree as CRA) and 3.081 msec (for scenarios using binary exponential back-off algorithm). As specified in DAVIC each TDMA frame is sub-divided into Poll time slots, Contention Slots(CS) and Reserve Slots(RS). However, the simulator works in contention mode only and it is believed that the use of polling will not affect the performance significantly (as explained in section 3.2.2). The size of poll, contention and reserved time slots is 68 bytes (53 bytes ATM cell plus 15 bytes radio header) as described in DAVIC recommendations. The performance is observed for two upstream data rates i.e., 2 Mbps (when using ternary tree) and 5.12 Mbps (when using binary exponential back-off). After the initial ranging process, users contend for bandwidth in the first available (selected) contention Slot (Polling may also be used for bandwidth request). The feedback of contention in “frame i ” is received in “frame $i+1$ ” (DAVIC specification). If bandwidth is not available then successful requests are queued at LMDS-hub (infinite request-queue models are assumed). Only one request per service ID (per user) can be outstanding at the LMDS-hub. Since DAVIC does not restrict the choice of the CRA we have examined its performance both using ternary tree collision resolution algorithm (CRA) and binary exponential backoff algorithm.

In the case of fixed slot allocation scheme, each frame consists of a fixed number of con-

tention and reserve slots with different ratio used for different types of traffic. The optimum fixed CS/ RS ratio for different traffic models has been discussed in their respective sections. With the optimal usage of observed traffic parameters (e.g., average request size, pending collisions, pending reservation requests, etc.), a dynamic CS to RS ratio scheme has been implemented for WWW traffic model and Batch-Poisson traffic model. All contention slots are clustered in the middle of the frame. For reasons of fairness and simplicity in a homogeneous traffic scenario, a round robin scheduling scheme has been implemented. For heterogeneous traffic scenarios a hierarchical-fair-queueing scheduling scheme has been used. A summary of the simulation parameters for DAVIC simulator is given in table 6-1.

Simulation Parameters	Traffic Models			
	WWW	Batch Poisson	Random Short	Heterogeneous
Upstream Channel Capacity (Mbps)	2, 5.12	2, 5.12	2, 5.12	2
Number of Active Terminals	200 - 3000	200,400		
Data and Contention slot size (bytes)	68			
Frame duration (msec)	3.264, 3.081			3.264
Contention slots: Data slots	1:2, 9:20 and variable	1:3, 7:22 and Variable	All Contention Slots	1:5
Collision Resolution Algorithm	Ternary Tree and Binary Exponential back-off			
Guard band and Preamble (bytes)	5			
Time Slots per Frame	12, 29 (for 2 Mb/s and 5.12 Mb/s respectively)			
Head-end Process delay	0			
Percentage of channel error	0%,5%,10%,20%			

Table 6-1: Summary of Simulation Assumptions For DAVIC

6.1.1.2 DAVIC Simulation Results for Noiseless Channel

As mentioned earlier, the DAVIC MAC does not limit the choice of the CRA. We have observed the performance of the DAVIC protocol under both the Ternary Tree algorithm and the Binary Exponential Back-off algorithm.

6.1.1.2.1 Simulated Performance Under Ternary Tree Algorithm

6.1.1.2.1.1 WWW Traffic Model

All users generate WWW-traffic and the traffic load is varied by changing the size of the user population. We have used a fixed CS/DS ratio of 1:2. This ratio is found close to optimum, because on average 3 CS are required for a single successful request and the average request size is 5 DS (which requires a CS/DS ratio of 3:5 or approximately 1:2).

The results for mean-access delay under WWW-traffic are shown in figure 6.1. The horizontal axis shows the aggregate traffic load and the vertical axis shows the mean-access delay. The continuous-line and the broken-line show the mean-access delay for fixed and dynamic (contention slot and data slot) slot allocation schemes respectively. As described in section 5.1, the WWW-traffic is highly variable which requires longer simulation runs. We run simulations for enough duration so that each user encounters a number of ON and OFF periods. On average each user generates a load of 0.083 Kbps and the traffic load is increased by increasing the size of user population.

Figure 6-1: Users Vs. mean delay for dynamic and fixed CS/ RS ratio.

As seen from figure that the mean-access delay remains practically constant for 2000 users under the fixed scheme and 3000 users under the dynamic scheme; beyond that it increases sharply. Although the load generated by 3000 users (in the dynamic scheme) is only 20% of the total link capacity the delays are high. The reason for this unusual behavior is that as the population size is increased beyond 3000 (for the dynamic slot allocation scheme) the load on the contention slots increases beyond the saturation limit and the collision multiplicity increases (figure 6-2). This increases the length of collision resolution interval (CRI) and consequently the request delays becomes high. The high mean -access mainly consists of high request delay and nominal queueing (scheduling) delay. As expected the use of the dynamic slot allocation scheme greatly improves the delay performance of the protocol.

Figure 6.2 shows the collision-multiplicity statistics for the dynamic slot allocation scheme for 3000 user population. It shows that from the allocated contention slots 95% are not used, 4% are used successfully and 0.61% face collision. Although the percentage of collisions is very small the collision-multiplicity (number of collided users in a contention slot) is quite high. This increases the duration of the collision resolution and hence the mean-access delay.

Figure 6-2: Collision Multiplicity for 3000 Users (Load = 18%) for Adaptive CS/DS ratio.

6.1.1.2.1.2 Batch Poisson Traffic Model

All users generate batch-Poisson traffic. Performance is measured in terms of mean-access delay. The following assumptions are made in addition to the assumptions of section 6.1.2.1.

- The ratio of contention slots to data slots is 1:3 (because on average we get one success per 3 CS and the average request size is 9 DS, this requires an optimum CS/DS ratio of 3:9 or 1:3).
- The user population is fixed i.e., 200 users.
- The load is varied by changing the mean message arrival rate of each user.

Figure 6.3 shows the performance of the MAC in terms of mean-access delay against the aggregate batch-Poisson traffic load. The increase in delay with the increase of load is observed to be small (below a load of 50%, which consists of information only). At a load of 10% (of link capacity), the mean-access delay is 10 ms and it increases to 25 ms for a load of 50%.

Figure 6-3: Load Versus Mean Access Delay with Batch Poisson Traffic for DAVIC

The reason for smaller delays is the large request size (on average 9 ATM cells) and moderate number of active users comparing to WWW traffic model (where average request size is 5 ATM cells and user population varies from 400 to 3000). Beyond a load of 55% the delay increases sharply, because the load on contention slots has reached its saturation region. Better results (low mean-access delay) may be observed with dynamic slot allocation scheme.

6.1.1.2.1.3 Short Random Traffic Model

All users generate Random-Short traffic and transmit their messages in the first available contention slot. Performance is measured in terms of mean-access delay, throughput and cell-delay variation. Immediate data transfer mode is used, i.e., if the information size is equal or less than 48 bytes then it can be transmitted using contention slots. The use of contention slots to carry information may be useful for delay sensitive applications (e.g., video game applications).

We make the following assumption in addition to the assumptions specified in section 6.1.2.1.

- All time slots of the frame are used as contention slots.
- The users wait for acknowledgment and retransmit their message if no acknowledgment or positive acknowledgment is not received.
- The size of user population is fixed (i.e., 200) and the load is varied by changing the message arrival rate.

- The load consists of only successful transmissions (the load of retransmission due to collision is not included).

It can be seen in the figure 6-4 that the mean-access delay is considerably low (less than 5 msec) for a load of 36%; beyond that the delay increases sharply.

Figure 6-4: Mean Access Delay with Random Short traffic For DAVIC

Since the protocol operates in immediate data transfer mode (no contention-reservation operation) therefore the performance is guided by the collision resolution algorithm. As we know that the maximum achievable throughput of ternary tree CRA with different variations ranges from 38% to 48% of link capacity. In frame based implementation (the one we have used), the maximum achievable throughput is relatively low (37% which is

approximately the same as in our simulation results). We observe from this traffic model that the link utilization is very low for this kind of traffic. This is because of the fact that each request consists of one ATM cell only. If a contention-reservation scheme is used in which the request size is large (i.e., large number of time slots or bandwidth is requested) then link utilization will improve as is the case of WWW-traffic and Batch-Poisson traffic. Figure 6.5 represents the histogram of packet mean-access delay. As shown in figure that majority of packets fall in the range of 2 msec mean-access delay.

Figure 6-5: Histogram of Packet Access Delay for Random Short Traffic

6.1.1.2.1.4 Heterogeneous Traffic Model

In this scenario there are two types of users: CBR (refer [11]) users and persistent-ABR users (for example, file transfer application). The performance of CBR traffic is measured

in terms of call-blocking probability, whereas the performance of batch-Poisson traffic is evaluated in terms of throughput. In addition to the general assumptions described in section 6.1.2.1 we make the following assumptions.

- There are 100 CBR users and each user generates 0.05 Erlang traffic load.
- There are 10 persistent-ABR users, each generates a minimum load of 0.083 Mbps.
- The upstream bandwidth is divided into three portions: CBR traffic and ABR traffic are allocated 42% each of the total link capacity and contention traffic is given 16% of the total bandwidth.
- The ABR traffic may utilize the unused portion of the CBR bandwidth but vice-versa is not true.
- Both CBR traffic and ABR traffic use the same contention slots for control messages.
- The CBR portion of frame may carry the maximum traffic of almost 5 Erlangs at 2% call blocking probability.
- Hierarchical scheduling is used for CBR and ABR traffic. Each CBR connection is assigned a separate queue at the hub, however all the ABR user have a single queue at hub. Round-robin scheduling is used for individual ABR connections.

The call blocking probability of CBR calls with varying traffic load is shown in figure 6-6.

With 42% link capacity reserved for CBR traffic, the LMDS hub can handle 10 simultaneous CBR calls. If the request for calls arrive when 10 calls are already in progress the call is rejected. The LMCS hub (with above assumptions) can support 5 erlang traffic at a call blocking probability of 2%. The simulation results shows that at 5 erlang load the call blocking probability is close to the theoretical calculations. As the traffic load is increased further the call blocking probability increases linearly till a load of approximately 7 erlangs after that it increases sharply.

Figure 6-6: Call Blocking Probability for CBR Traffic

The ABR connections are allocated 0.83 Mbps out of the 2 Mbps link capacity. This means that when the CBR calls uses all of its assigned share the ABR users will receive a minimum of 0.83 Mbps. In case when the bandwidth reserved for CBR connections is idle then the ABR connections can benefit from it. The simulation results shows that when the CBR traffic load is low, the scheduler assigns the idle slots to the ABR users and the

throughput of ABR traffic is higher than its share (figure 6-7). As the CBR traffic load increases the ABR throughput decreases until it reaches its guaranteed rate of 0.83 Mbps. Hence, the hierarchical scheduling supports real time connections with required QoS and at the same time efficiently utilizes idle bandwidth to support non-real-time connections.

Figure 6-7: Aggregate Throughput of ABR Traffic

6.1.1.2.2 Simulated Performance Under Binary Exponential Back-off Algorithm

6.2.1.2.2.1 WWW Traffic Model

All users generate WWW-traffic and the traffic load is varied by changing the size of the user population. The performance is observed for fixed ratio of contention to reserve slots of 9:20. As seen from figure that the mean-access delay remains practically constant for 1800 users beyond that it increases sharply although the traffic load is low (figure 6-9).

The reason for this unusual behavior is that as the population size is increased beyond 1800, the load on the contention slots increases beyond the saturation limit and the collision multiplicity increases (figure 6-13). This increases the length of collision resolution interval (CRI) and consequently the request delays becomes high (figure 6-10 and figure 6-11). The high mean -access delay mainly consists of high request delay and nominal queueing (scheduling) delays.

The delay variation is moderate (figure 6-12) because of low load conditions. Furthermore, the mean-access delay (for 1800 user population) less than 5 msec are observed with probability 0.98 and less than 10 msec with probability 1 (figure 6-14).

Figure 6-8: Mean Access Delay with WWW traffic for DAVIC

Figure 6-9: Mean Access Delay with WWW traffic For DAVIC

Figure 6-10: Mean-Request Delay with WWW traffic for DAVIC

Figure 6-11: Mean-Request Delay with WWW traffic for DAVIC

Figure 6-12: Coefficient of Delay Variation with WWW traffic for DAVIC

Figure 6-13: Collision Multiplicity with WWW traffic for DAVIC

Figure 6-14: Probability Distribution Function of Mean Access Delay with WWW traffic for DAVIC

6.1.1.2.2.2 Batch Poisson Traffic Model

The following assumptions are made in addition to the assumptions of section 6.1.2.1.

- The ratio of contention slots to data slots is 7:22.
- The user population is fixed i.e., 400 users.
- The load is varied by changing the mean message arrival rate of each user.

Figure 6.15 shows the performance of the MAC in terms of mean-access delay against the aggregate batch-Poisson traffic load. The increase in delay with the increase of load is observed to be small (below a load of 3.8 Mbps). Beyond a load of 4 Mbps the delay increases sharply, because the load on contention slots has reached its saturation region.

The improvement in the performance through the adaptive CS/DS ratio scheme is observed to be insignificant (figure 6-15).

Figure 6-15: Mean-Access Delay With Batch-Poisson Traffic For DAVIC

6.1.1.2.2.3 Short Random Traffic Model

Following are few more assumptions in addition to those specified in section 6.1.2.1.

- All time slots of the frame are used as contention slots.
- The users wait for acknowledgment and retransmit their message if no acknowledgment or positive acknowledgment is not received.
- The size of user population is fixed at 400 and the load is varied by changing the message arrival rate.

It can be observed from figure 6-17 that the mean-access delay is considerably low (less than 10 msec) for a load of 3 Mbps; beyond that the delay increases sharply. Since the protocol operates in immediate data transfer mode (transfer of data in the contention slots) therefore the performance is guided by the collision resolution algorithm. We observe from this traffic model that the link utilization is very low for this kind of traffic (figure 6-16). This is because of the fact that each request consists of one ATM cell only. If a contention-reservation scheme is used in which the request size is large (i.e., large number of time slots or bandwidth is requested) then link utilization will improve as is the case of WWW-traffic and Batch-Poisson traffic.

Figure 6-16: Throughput Performance with Random-Short Traffic for DAVIC

Figure 6-17: Mean-Access Delay with Random-Short Traffic for DAVIC

6.1.3 DOCSIS Simulator and Results Discussion

6.1.3.1 DOCSIS Simulation Model

The following simulation model was used to examine the performance of the DOCSIS MAC Standard.

Although no fixed frame structure is specified in DOCSIS standard, we assume that the upstream channel is divided into fixed length TDMA frames. Each TDMA frame is further divided into a number of mini-slots whose size depends on the upstream data rate and physical parameters. For upstream channel capacity of 5.12 Mbps and QPSK modulation, the size of mini-slot comes out to be 8 bytes. Each frame may consists of a number of contention mini-slots (CMS) and reserve data slots (DS). The CMS are clustered at the middle of the frame. A number of mini-slots are combined to form ATM PDU and Variable Length PDU for ATM TS and IP traffic respectively. After initial ranging the user listens to the downstream CMS allocation message which includes the number of CMS in next frame, the Data-Start-Back-off window and Data-End-Back-off window parameters. The size of data start back-off window and data-end backoff window is assumed to be '4' and '8' respectively. The user selects randomly a CMS from the Data-Start-Backoff window and transmits its request in the chosen contention CMS. The feedback of contention in "frame i" is received in "frame i+1". If bandwidth is not available then successful requests are queued at LMDS-hub (infinite request-queue models is presently assumed). Only one request per service ID (per user) can be outstanding at the LMDS-hub. In the case of collision, the Binary Exponential Back-off algorithm is used to resolve the collisions (DOCSIS

Specification). In case of fixed slot allocation scheme, each frame consists of a fixed contention and reserve slots. The optimum fixed CS/RS ratio for different traffic models has been discussed in their respective sections. With the optimal usage of observed traffic parameters (e.g., average request size, pending collisions, pending reservation requests, etc.), an adaptive CMS to DS ratio scheme has been implemented for WWW traffic model. For reasons of fairness and simplicity in a homogeneous traffic scenario, a round robin scheduling scheme has been implemented.

Simulation Parameters	Traffic Models		
	WWW	Batch Poisson	Random Short
Upstream Channel Capacity (Mbps)	5.12		
Number of Active Terminals	400 - 4800	400	
Mini- slot size (bytes)	8		
Data start back-off window	4		
Data end back-off window	8		
Frame duration	3msecs		
Contention slots: Data slots	15:21	10:22	24:0, 35:17
Collision Resolution Algorithm	Binary Exponential back-off		
Guard band and Preamble (bytes)	5		
Head end Proceession delay	0		
Size of Data slots (bytes)	80		
Size of CMS (bytes)	16		

Table 6-2: Summary of Simulation Parameters for DOCSIS

6.1.3.2 DOCSIS Results for Noiseless Channel

6.1.3.2.1 WWW Traffic Model

In this scenario the load is varied by changing the size of user population. The performance is studied for a fixed contention slot to reserve slot ratio of 15:21 and adaptive CS/DS ratio scheme. It can be observed (figure 6-18) that the delay remains practically constant for the user population of 2400 users beyond that the delay increases sharply. This is because the load on the contention slots has increased beyond its breakdown region and the higher collision multiplicity (as explained in section 6.1.1.2.1.1). Figure 6-19 indicates that although the load on the reserve slots is low but the delays are high which is because of high collision multiplicity. It can also be observed from figure 6-21 that the delay variance is moderate because of low load conditions.

Figure 6-18: Mean-Access Delay with WWW traffic for DOCSIS

Figure 6-19: Mean-Access Delay with WWW traffic for DOCSIS

Figure 6-20: Mean-Request Delay WWW traffic for DOCSIS

Figure 6-21: Coefficient of Delay Variation with WWWW traffic for DOCSIS

6.1.3.2.2 Batch Poisson Traffic Model

As this traffic can be transported using either ATM or VL PDU hence we observe the performance of the protocol for both transport schemes (refer to [12], [15]).

a) ATM PDU

In this scenario the arriving packets are segmented into ATM cells. The segmentation and associated overheads (FEC, preamble, guard band, quantization) are given in table 6-4. The load is increased by increasing the cell arrival rate for a fixed size user population of 400. The performance is tested for fixed ratio of contention slots to reserve slots of 10:22. Figure 6-22 shows the mean-access delay versus global offered load (aggregate user traffic load). The increase in delay with the increase in load is not significant i.e., the delay is

less than 20 msec for a load of 4 Mbps or less. The reason for this behavior is that the average request size is large (9 ATM cells) and the user population is low (400) comparing to WWW traffic (average request is 5 ATM cells and load is increased by increasing user population). This results in low contention load and low request delays (figure 6-22).

The queuing delays are also low because the load on reserve portion of bandwidth is still lower (4 Mbps) than its share of bandwidth (4.3 Mbps). Beyond a load of 4 Mbps the delay increases exponentially because of breakdown of the CRA and the higher queuing delays. The theoretical calculations (table 6.5) shows that the upper bound on the effective throughput efficiency is 55%. The performance of MAC in terms of effective throughput is shown in figure 6-23. The simulation results shows that the maximum achievable effective throughput is 50% of the link capacity or 55% of reserve portion of bandwidth, which agrees with theoretical analysis.

It can be observed from figure 6-24 that the delay variance increases with load. The probability distribution function of the mean-access delay (for a 80% load) is shown in figure 6-25). It can be seen that mean-access delay remains lower than 50 msec with a probability of 0.98 and less than 90 msec with probability 1.

Figure 6-22: Mean-Access Delay with Batch-Poisson traffic for DOCSIS

Figure 6-23: Mean-Access Delay with Batch-Poisson traffic for DOCSIS

Figure 6-24: Coefficient of Delay Variation with Batch-Poisson traffic for DOCSIS

Figure 6-25: Probability Distribution Function of Mean Access Delay with Batch-Poisson traffic for DOCSIS

b) VL PDU

The use of VL PDU can increase the effective (information) throughput because of low ratio of information to MAC and physical overheads as compared to ATM PDU (table 6-4). Because of FEC limitations on the maximum size of PDU, we segment the VL-PDU into suitable lengths PDU as shown in table 6-3. Both fixed and variable coding schemes can be used with varying degree of efficiency and complexity, we have used the later. Similar trends can be observed for mean-access delay, request delay, collision multiplicity, coefficient of delay variation and probability distribution function of mean-access delay as were observed for ATM transport mode of operation. The major difference is higher effective throughputs in VL mode of operation than in ATM TS (compare figure 6-23 and 6-26). The average effective throughput efficiency is almost 78% in VL PDU case whereas it is approximately 55% in ATM PDU operation. Hence, for similar performance we can achieve higher effective throughputs using VL PDU for traffic types which generates VL packets. For ATM TS, the upstream frame is divided into a number of time slots which can

Segmented Packet Size	Coding	Code Rate
64	(78, 64) $\leftrightarrow$ (127, 113)	0.82
81	(102, 81) $\leftrightarrow$ (127, 106)	0.79
102	(126, 102) $\leftrightarrow$ (255, 231)	0.81
128	(152, 128) $\leftrightarrow$ (255, 231)	0.84
205	(253, 205) $\leftrightarrow$ (255, 207)	0.81

Table 6-3: Segmentation and Coding of VL PDU

encapsulate one ATM cell and other overheads. Therefore, each ATM cell is transported as single entity in continuous transmission. However, in VL transport the upstream frame is

divided into a number of mini-slots and one VL PDU may be required to transmit at different times and hence requiring separate guard band and preamble. We have used guard band and preamble with each VL PDU only once. Hence, the reported results gives the best possible performance for VL PDU and worst case performance for ATM PDU

Offd. Pkt. Size	Segmentation (Bytes)	VL PDU (Information + FEC + MAC Header + Guard Band + Preamble + Quantization)	Segmentation	ATM PDU
64	1×64	$64 + 14 + 6 + 1 + 4 + 7 = 96$	$(1 \times 48) + (1 \times 16)$	2×80
128	1×128	$128 + 24 + 6 + 1 + 4 + 5 = 168$	$(2 \times 48) + (1 \times 32)$	3×80
256	2×128	2×168	$(5 \times 48) + (1 \times 16)$	6×80
512	$(2 \times 205) + (1 \times 102)$	$2(205 + 48 + 6 + 1 + 4 + 3)$ 2×256	$(10 \times 48) + (1 \times 32)$	11×80
1024	$(4 \times 205) + (1 \times 204)$ $\cong 5 \times 205$	$102 + 24 + 6 + 1 + 4 + 7 = 144$	$(21 \times 48) + (1 \times 16)$	22×80
1516	$(7 \times 205) + (1 \times 81)$	$7(205 + 48 + 6 + 1 + 4 + 3) +$ $1(81 + 21 + 6 + 1 + 4 + 7)$ $= (7 \times 256) + (1 \times 120)$	$(31 \times 48) + (1 \times 128)$	32×80

Table 6-4: Segmentation, Physical and MAC overheads of VL PDU and ATM PDU

	Offered Pkt. Size (Bytes)	VL PDU (Bytes)	VL PDU efficiency	ATM PDU	ATM PDU efficiency
	64	96	0.66	160	0.4
	128	168	0.76	240	0.533
	256	336	0.76	480	0.533
	512	656	0.78	880	0.58
	1024	1280	0.8	1760	0.58
	1516	1912	0.79	2560	0.59
Average	368.04	471.6	0.78	664	0.554

Table 6-5: Throughput efficiency of VL PDU and ATM PDU

Figure 6-26: Effective Throughput for Batch-Poisson Traffic using VL PDU for DOCSIS

Figure 6-27: Mean-Access Delay For Batch-Poisson Traffic using VL PDU for DOCSIS

Figure 6-28: Collision Multiplicity
Batch-Poisson traffic for DOCSIS

Figure 6-29: Probability Distribution
Function of Mean-Access Delay Batch-
Poisson traffic for DOCSIS

6.1.3.2.3 Short Random Traffic Model

a) Immediate Data Transfer Mode:

Following assumptions were made for this scenario.

- All time slots of the frame are used as contention slots.
- The users wait for acknowledgment and retransmit their message if no acknowledgment or positive acknowledgment is not received.
- The size of user population is fixed at 400 and the load is varied by changing the message arrival rate.

It can be seen in figure 6-30 that the mean-access delay is low till a load of 2.5 Mbps (almost 50% of link capacity). When the load is increased beyond 2.5 Mbps the delay increasing sharply and the delays becomes significantly high as the load is increased beyond 3.5 Mbps (almost 70% of link capacity). Since the protocol operates in immediate mode of operation hence the performance results are guided by the CRA i.e., binary exponential backoff algorithm. The maximum achievable throughput is close to 31% (figure 6-31). Although lower delays are observed but the link utilization is also low which can be improved through the use of contention-reservation operation.

Figure 6-30: Mean-Access Delay with Short Random Traffic using Immediate Data Transfer Mode For DOCSIS

Figure 6-31: Throughput with Short Random Traffic using Immediate Data Transfer Mode For DOCSIS

b) Contention-Reservation Mode:

A fixed ratio of CMS to DS of 35:17 was used. The mean access delay at moderate loads (2Mbps or lower) are comparable in immediate data transfer mode and contention reservation mode. Beyond this limit the delays increases sharply in former and slowly in later case. This is because of a large number of contention slots in contention reservation mode then immediate data transfer mode in which CS are of bigger size and carries the actual information. It can also be observed that the throughput in immediate data transfer mode drops sharply (figure 6-31) beyond the breakdown of CRA. Whereas in contention-reservation mode of operation the throughput stabilizes at the reserve portion of the link capacity (figure 6-33).

Figure 6-32: Mean Access Delay for Short Random Traffic (cont-res mode)

Figure 6-33: Throughput for Short Random Traffic (cont-res mode)

6.1.4 Simulation Results for Noisy Channel

All practical communication media suffer from noise problem. In this regard, wireless medium is considered to be the most unreliable channel of all other communication mediums. Especially, this problem becomes severe for wireless systems designed to operate at 20 GHz to 60 GHz bands (for example, LMCS). To reduce its effect to acceptable level, forward error correction (FEC) schemes are employed which shape the original data to combat the noisy channel.

The channel conditions (for example error probability and power control) of individual LMCS-users in a cell may differ from each other because of their geographical locations. As a result channel bit error rate (BER) and cell loss ratio (CLR) would be different for different LMCS-users. Due to this reason, the QoS provided to different LMCS-users will vary, for example a LMCS-user with high BER (say 10^{-3}) will see higher access delay and CLR than another LMCS-user with low BER (say 10^{-6}). In order to examine the QoS provided to different LMCS-users, sophisticated channel models are required. In the absence of these models, we assume that all LMCS-users have identical channel conditions and study the average performance metrics as described below.

The following assumptions were made to study the effect of channel noise. The FEC in downstream channel is strong enough to correct all errors in downstream. We consider that all errors in upstream channel are detected by the hub but they could not be corrected. The errors occur as percentage of transmitted request or data cells. Also same FEC is used for data and control channel. The errors in contention slots are treated as collisions. Whereas,

if a data cell is found to be in error then that cell is discarded and selective ARQ (automatic repeat request) is used to recover it. We examine in the following section the effects of channel errors on the performance of the DAVIC MAC protocol.

The effects of channel errors on the performance of the DAVIC MAC for Batch Poisson traffic can be seen in figure 6-34 for various percentage of errors. The horizontal-axis shows the offered load and the vertical-axis represents the mean-access delay. It can be observed that the difference in the mean-access delay for various error ratio is insignificant for lower loads. This difference increases for higher load conditions. The reason for this behavior is that at lower load conditions, enough reserve slots and contention slots are available for the retransmissions of the data cells found in error. On the other hand, at higher loads, the channel is already stressed and it takes longer time to retransmit the data cells and resolve the collision.

The performance degradation is relatively higher in the Random-Short traffic scenario (figure 6-35). This is because the DAVIC operates in the immediate data transfer mode in which the load on the contention slots is significantly higher than Batch Poisson traffic.

Figure 6-34: Effect of Channel Errors on DAVIC For Batch-Poisson Traffic

Figure 6-35: Effect of Channel Errors on DAVIC For Short Random Traffic

6.1.5 Performance Comparison of Candidate MACs

6.1.5.1 WWW Traffic Model

The comparative performance of the two protocols with WWW traffic model is shown in figure 6-36. The difference in the mean-access delay of the two protocols at lower load conditions is not significant. This is because of low load on contention slots. As the size of user population increases beyond 1800 users the delays increase sharply in case of DAVIC whereas this breakdown comes around 2400 users for DOCSIS. The reason for this behavior is the difference in the size of the contention slots in the two protocols. For each contention slots in DAVIC, the DOCSIS can have almost 4 contention slots. Hence, the

DOCSIS protocol can support higher contention load than the DAVIC and therefore, can give better efficiency.

Figure 6-36: Comparative Performance in WWW Traffic

6.1.5.2 Batch Poisson Traffic Model

Figure 6-37 gives the comparative performance of both MAC protocols. The solid curve, and dotted curve show the performance of DAVIC and DOCSIS protocols respectively. It can be observed that the mean-access delay is almost the same for low load conditions. The difference starts to appear beyond load of 2 Mbps. For same contention share of link capacity DAVIC has fewer contention slots than DOCSIS, hence the breakdown of CRA

reaches earlier in DAVIC. Hence, under identical conditions a slightly higher throughput can be achieved in DOCSIS.

Figure 6-37: Comparative Performance for Batch-Poisson Traffic

6.1.5.3 Short Random Traffic Model

In this scenario the results for DAVIC includes when it operates in immediate data transfer. Whereas the results of DOCSIS includes both for immediate data transfer and contention-reservation mode. In immediate data transfer mode the performance of the two protocols is identical at lower load conditions (1.5 Mbps or lower). As the load is increased beyond 1.5 Mbps the DAVIC performs slightly better than DOCSIS. The reason for this behavior is that for the same frame size DAVIC has more contention slots per frame than DOCSIS (68 bytes in DAVIC and 80 bytes in DOCSIS) and hence can support more load.

Figure 6-38: Comparative Performance For Short-Random Traffic

Since DOCSIS can support smaller size contention slots and hence is expected to give higher throughput in contention-reservation mode than immediate mode (figure 6-38). In contention-reservation operation, for 30% of link capacity assigned to CMS we can have more CMS than the number of slots in immediate mode (each slot gives 5 CMS). The remaining 70% of the link capacity can be used for reservation portion and hence higher throughput can be achieved.

Chapter 7

Conclusions And Future Work

7.1 Summary of Thesis

The main objective of this study was to find a suitable MAC protocol for LMCS/ LMDS networks which can provide bandwidth on demand and QoS guarantees without wasting link resources. For this reason we selected the LMCS specific DAVIC MAC recommendations and DOCSIS MAC standard (HFC specific MAC which will provide similar services at comparable capacity) in order to compare their performance. This study will help the LMCS system designer to make the choice of particular MAC based on his target service market.

In order to achieve our objective we built two separate simulators for the DAVIC MAC and DOCSIS MAC standard in C++. These simulators are generic and can be used with: different traffic models, variable user population and load conditions, a number of data cell scheduling scheme to analyze their suitability with the MAC, any dynamic slot allocation (of CMS and data cells) scheme, variable upstream frame size. Since the DAVIC does not restrict the choice of Collision resolution algorithm (CRA), its performance has been examined under ternary tree CRA (for comparison with IEEE 802.14) and binary exponential CRA (for comparison with DOCSIS) for noisy and noise-free channels.

For a comprehensive study of both protocols we used a variety of homogeneous and heterogeneous traffic models. These traffic models highlight the key characteristics of the two protocols (for example the size of contention slot and piggybacking) which makes the comparative study more meaningful. The two protocols are compared in terms of mean-access delay and throughput, however the reported results also include probability distribution function of mean-access delay, coefficient of delay variation, call blocking probability (for CBR calls) and collision multiplicity statistics.

The comparative performance improvement through the use of dynamic slot allocation of contention and data slots has also been studied. Moreover, the application of ATM scheduling schemes in wireless networks is also described. A few scenarios which incorporates the effects of channel errors has also been presented.

7.2 Summary of Results

One of the major causes of the difference in the performance of the two protocols is the size of the contention slot. DAVIC uses a fixed size (68 bytes) contention slot, whereas the DOCSIS utilizes contention mini-slot whose size depends on the upstream data rate and the physical parameters. In our simulations we used a contention mini-slot of 16 bytes. Therefore, for the same percentage of bandwidth in the two protocols reserved as contention portion, the DOCSIS MAC will have higher number of contention slots than the DAVIC and as a result can support more contention load.

Hence for traffic types which generates high contention load, the breakdown region reaches earlier in the DAVIC MAC. It was observed in the case of WWW (World Wide Web) traffic model where the performance of the two protocols was identical at moderate load conditions. However, the breakdown of DAVIC protocols reached for 2000 user population and this breakdown occurred for 2600 users in case of the DOCSIS.

For the traffic types which require fewer contention slots we may use the same number (and not the same percentage of bandwidth) of contention slots in the two protocols. This results in greater reserve bandwidth in the DOCSIS than the DAVIC. As a consequence, the performance in terms of mean-access delay are comparable in the two protocols but slightly higher throughputs are achieved in the DOCSIS (because of more reserve slots). This observation was verified through the Batch-Poisson traffic. The minimum average request size (9 ATM cell) in this traffic is higher than WWW traffic (minimum average request size is 5 ATM cell and load is increased by increasing user population) and requires fewer contention slots. Similar mean-access delay and slightly higher throughputs are achieved in DOCSIS than the DAVIC.

Another characteristic which provides better efficiency for DOCSIS is the support of VL PDU with a smaller slot granularity. This gives the flexibility to transmit VL packets (for example ethernet traffic) thereby reducing the quantization overhead. Furthermore, VL packets (the maximum length is governed by the FEC limitations) can carry more information per packet than ATM PDU and consequently minimize the high percentage of physical overhead per PDU. Hence, we run simulations for the two modes of transportation (ATM and VL) for the DOCSIS and observed that for similar throughputs in the two

modes the average efficiency of actual information transfer (or effective throughput) was higher in case of VL PDU (78% in VL PDU and 55% in ATM PDU).

One factor which gives better link utilization in the case of single ATM cell transfer (for example voice traffic and video games applications) is the size of the MAC header. The DOCSIS MAC uses 6 bytes MAC header on top of ATM cell (single MAC header may be used for a number of ATM cells). Whereas, DAVIC uses a pure ATM approach and does not require extra overhead than the ATM header. As a result the size of time slot (in case of ATM transport) is larger in the DOCSIS (80 bytes in our simulations) than in the DAVIC (68 bytes). Hence, the efficiency per ATM PDU is higher in the DAVIC ($48/68 = 70\%$) than the DOCSIS ($48/80 = 60\%$). The comparison on this basis was done in the Short-Random traffic and the heterogeneous traffic. In case of the Short-Random traffic (immediate data transfer), for the same upstream link capacity and frame duration the number of time slots are higher in the DAVIC (29) than in the DOCSIS (24). In immediate data transfer mode, the protocols operate only in contention mode and the performance is guided by the CRA. Therefore, for similar maximum throughput (approximate 32% of link capacity) the bandwidth efficiency (or effective throughput) is higher in the DAVIC. However, in contention reservation mode for this traffic we can get higher throughput in the DOCSIS (at higher delays) because of the smaller size contention slots.

For additional bandwidth requests the DOCSIS may use the optional piggy-backing field. Hence for traffic types (or a mixture of traffic types) with higher contention load and large request size (for example a mixture of Batch-Poisson and Short-Random

traffic) the use of piggy-backing reduces the load on contention slots and results in improved performance of the DOCSIS MAC.

The effects of channel errors on the DAVIC MAC performance under Batch-Poisson traffic and Short-Random traffic were examined and it was found that the performance degradation is higher in the later. A more detailed study of the robustness of the two protocols under channel errors requires further study.

We used simple dynamic slot allocation (of contention reserved slots) schemes to compare the performance improvement of both MAC protocols. It was observed that this improvement in performance is comparable in the two protocols (this was observed in case of WWW traffic).

As LMCS networks will provide similar services as those offered by the wireline networks therefore it is required to provide similar QoS guarantees. We also investigated the implementation of ATM scheduling schemes (proposed for wireline networks) in wireless networks. It was observed in heterogeneous traffic scenario (a mixture of CBR traffic and persistent ABR traffic) that through the use of hierarchical scheduling better link utilization at committed QoS guarantees can be achieved.

7.3 Conclusions

In order to make a fair comparison of the two protocols, we took similar simulation assumptions for both protocols and tested their performance for a variety of homogeneous and a heterogeneous traffic models under noise-free and noisy channels. It can be concluded from the reported results that the performance of the DOCSIS was better under most of the scenarios (WWW traffic, Batch-Poisson traffic and contention-reservation mode in Short-Random traffic). While for similar mean-access delay the bandwidth efficiency is slightly higher in the DAVIC for Short-Random traffic (immediate data transfer mode). The smaller size contention slot, support of VL PDU, piggy-backing for additional bandwidth requests and large size MAC header in the DOCSIS MAC are the main differences with the DAVIC MAC which cause the above mentioned performance difference. The DAVIC 1.2 recommendations provide a total solution for LMCS system engineering whereas the DOCSIS MAC is HFC specific, hence certain modifications would be needed in order to use the later in LMCS networks. However, the final choice of a protocol depends on the choice of the target service market and system complexity.

With simple scenarios of channel errors it was observed that both protocols are equally affected by the noise (more detailed analysis is required). Finally, through the use of ATM scheduling better link utilization and committed QoS guarantees can be achieved.

7.4 Recommendations for Future Research

In this comparative study we tried to cover most of the important issues in the two protocols. However, some issues which need further research are discussed as follows.

- We examined the performance of both protocols under binary exponential algorithms. It is expected that their performance (stability and throughput) would be improved through the use of p-persistent CRA. The relative performance improvement needs to be examined.
- As we used round robin scheduling in homogeneous traffic scenarios, hence in the case of ATM TS for the DOCSIS we used MAC header with each transmitted ATM cell. However, the DOCSIS protocol allows to transmit a number of ATM cells requiring only a single MAC header (as a result also requiring preamble and guard band only once). This reduces the average amount of overhead per cell and as a result the bandwidth efficiency and effective throughput will improve. The relevant improvement requires further study.
- Piggy-backing may be used for additional bandwidth request in the DOCSIS and IEEE 802.14. Additional 4 bytes (as compared to 4 bits in IEEE 802.14) are needed for piggy-backing field with each PDU. While the use of piggy-backing field is optional in the DOCSIS, this field is fixed in IEEE 802.14. Hence, for a mixture of CBR and VBR traffic where the former does not need piggy-backing the DOCSIS MAC might give better efficiency than IEEE 802.14.

- We considered simple scenarios of channel errors. A more detailed and comprehensive study of the effects of channel errors on the MAC performance is another area which requires more research.
- We used a simple dynamic slot allocation (of contention and reserved slots) scheme to show the improvement in performance through these schemes. A more general and sophisticated scheme might be devised for optimum results.
- The issues related to the scheduling of data cells (for example queuing delays and fairness) is another area of interest for further research.
- We looked into the upstream performance of the two protocols in which we assumed that there is no congestion in the downstream direction. The study of both the upstream and the downstream will give a more detailed picture of the two protocols.
- In our study we assumed all users have equal priority to access the contention slots. For scenarios such as CBR calls (where the call blocking due to unavailability of control channel will increase the total call blocking probability) and real-time VBR connections (which require tighter delay bounds) a priority scheme to access the contention slot may be implemented ([16]).

- The end-to-end (call originating LMCS-hub, subsequent wireline switches and the egress LMCS-hub) performance of the protocol will provide better picture to the system designers.

Appendix -1

Cell Arrival / Departure Algorithms

A1.1 Cell Arrival Algorithm

The flowchart of cell arrival algorithm is given in figure 4. Whenever a cell reaches its HOL position, the virtual clock updates its virtual time function and HOL time stamp. A cell can reach the HOL position either due to the cell transmission from this buffer or an arrival at an empty buffer. The HOL stamp value and virtual time function for this connection are updated as follows;

$$S_{VC}^i(t) = \max\left\{F_{VC}^i(t), F_{VBR}(t)\right\},$$

$$F_{VC}^i(t) = S_{VC}^i(t) + \frac{1}{\omega_i}.$$

Note that due to the service hierarchy the HOL-stamp value is calculated with respect to the virtual time function of the VBR-server, $F_{VBR}(t)$, rather than the global time function of link server, $v(t)$. If all the real-time connection buffers are empty and VC^i HOL cell is the only cell in the VBR server, then the VBR server parameters must also be updated as shown below;

$$S_{VBR}(t) = \max\{F_{VBR}(t), v(t)\},$$

$$F_{VBR}(t) = S_{VBR}(t) + \frac{1}{\Lambda}$$

The updates for the ABR connection are done in a slightly different manner. The HOL-stamp value, $S_{ABR}(t)$, and virtual time function, $F_{ABR}(t)$, are updated only if the arriving HOL cell is the only HOL cell amongst both RM cell and data buffers. The updates are done as follows;

$$S_{ABR}(t) = \max\{F_{ABR}(t), v(t)\}$$

$$F_{ABR}(t) = S_{ABR}(t) + \frac{1}{\Theta}$$

No updates are required for cells arriving at non-empty buffers (both VBR and ABR), since only HOL cells are considered for transmission.

Figure 4: Cell Arrival Algorithm

A1.2 Cell Departure Algorithm

The flow chart of cell departure algorithm is shown in figure 5. At the end of each time slot cell departure algorithm is invoked. If buffers are not empty then the link server picks the cell from server (VBR or ABR) which has smaller HOL-value with all ties being resolved in favor of VBR traffic. If VBR server has the smaller HOL value, then the HOL cell is extracted from the VC^i which has the minimum HOL value. The global virtual time function is updated with the HOL stamp of the VBR server. Furthermore, the virtual time function, $F_{VC}^i(t)$, of the respective connection is updated in the same manner as in the cell arrival case. Whereas the HOL stamp value is updated in a slightly different way. If there are additional cells in the VC^i buffer, the update is the same as in the cell arrival case. Otherwise, the HOL stamp value is set to a very large value (Infinity), so that it is removed from further contention (i.e. $S_{VC}^i(t) = \infty$). In a similar manner updates are made for $F_{VBR}(t)$ and $S_{VBR}(t)$. The case of ABR server is a bit different since RM cells are given service priority, therefore, if an RM cell is waiting it is served first. The global virtual time function, $v(t)$, is then set to the HOL stamp value of the ABR server, $S_{ABR}(t)$. The updates for $S_{ABR}(t)$ and $F_{ABR}(t)$ are done in the same way as in cell arrival algorithm, except the case when both RM-buffer and data-buffer are empty. In such a case the ABR server is removed from contention by setting its value ∞ .

Figure 5: Cell Departure Algorithm

Appendix - 2

Description Of Simulator

The DAVIC and MCNS MAC simulators are implemented using C++ language. Powerful object-oriented features of C++ provide us the flexibility to break our simulator into different modules and classes. The modules used in our simulators are:

1. Constants and Global variables
2. Random class
3. Packet class
4. Queue class
5. WWW traffic class
6. Batch-Poisson traffic class
7. Short-Random traffic class
8. CBR-traffic class
9. Terminal class
10. Scheduler class
11. CRA class
12. Slot_Allocator class
13. Base-station class
14. Statistics class
15. Main program

A2.1 Constants and Global variables

A list of constants required during the simulation e.g. slot duration, load variation, maximum number of terminals etc. are maintained in a separate header file (Constants.h). This file is included in other file whenever some constant is needed. Moreover, there are some variables which are to be known by many interacting modules of the program and they are also defined in a separate header file (GlobalVar.h).

A2.2 Random class

This class acts as random number generator for our application. It is used for random mechanisms for example generation of different traffic and the selection of contention slots. The random number generator may use time/ integer numbers as initial seed so providing nearly true random behavior for each different run of the simulation. The random numbers can be obtained in different ways:

- Integer random number (0.range)
- Exponential random numbers

A2.3 Packet class

It signifies the packet structure generated by the traffic sources. A packet represents an ATM cell or VL packets in our application. The structure of each packet is as follows:

- Time: serves as packet generation time-stamp
- Source: represents source address
- Destination: represents destination address

A2.4 Queue class

Sources generates packets (ATM cells) which are stored in a queue maintained by such sources themselves and intermediate switches. To fulfill queue requirement, we defined Queue class. It is a simple linked-list of packets and provides standard functions for list manipulation such as add, remove, read, length etc.

A.2.5 WWW traffic Class

It represents a WWW source and generates the requests based on the model in [54]. It generates packets during the source ON period and stores them in the terminal queue which invoked the WWW traffic source. It also passes to the terminal class the OFF-period duration and the terminal remains idle (does not generate packets) during that time and after that again invokes the WWW class.

A2.6 Batch-Poisson class

It represents the Batch-Poisson traffic described in [55] and generates VL packets according to the distribution given in [55]. It passes the generated packets to the terminal class which invoked this process.

A2.7 Random_Short class

This class generates ATM cells according to the Poisson process and stores them in the respective terminal.

A2.8 CBR class

This class initiates a CBR call at a given call arrival rate and also generates the call holding time. If the call is accepted by the LMCS-hub, it generates packets at a constant (64 Kbps) rate. In case of call rejection, it reschedules the call.

A2.9 Terminal class

It represents a fixed wireless user. While active, a terminal runs an application program (homogeneous or heterogeneous) with the help of mentioned traffic models. The packets generated by the traffic model are stored in this class and waits for bandwidth allocation from the base-station. When the upstream bandwidth is required, it uses random class to select the available contention slot and transmits data when the bandwidth is assigned by the Base-station class.

A2.10 Scheduler class

It is responsible for the assignment of available data slots among the requested users. In case of homogeneous traffic, the scheduler assigns the available data slots in round-robin fashion. For HFQ scheduling (used in heterogeneous traffic scenario), it implements cell arrival and cell departure algorithms. Cell arrival algorithm is invoked when a cell enters a buffer while cell departure algorithm is used at the start of each time slot.

A separate queue is maintained with its associated parameters for each real-time connection. All non-real-time connections are aggregated into a single buffer whose respective

parameters are also maintained by the scheduler. Standard OO methods to “Set” and “Get” attributes/variables are also implemented in this class

A2.11 Collision Resolution Class

The purpose of this class is to initiate the collision resolution process. In case of tree this class is part of the Base-station class, while in the case binary exponential CRA it is distributed (functions in all terminal). It takes input parameters from the base-station class (for example, the number of contention slots in the next frame).

A2.12 Slot_Allocator class

It decides the number of contention and data slots in the coming frame based on the information provided by the base-station class.

A2.13 Base-station class

It is responsible for the collision resolution and bandwidth assignment to the requested terminals. Its sub-classes include: Slot_Allocator class, Scheduler class and Collision_Resolution class.

A2.14 Statistics class

This class is used to gather required simulation statistics (results provided by different modules) along the simulation run. In order to maintain statistical data, a large number of variables are used with appropriate set/get functions. Final statistics are saved in an output

file “TrafficType_Sim_Results.txt” which can be consulted later on.

A2. 15 The MAIN Program

All required bits and pieces (mentioned above) for a given scenario fit together in the main program “DAVIC_Simulator.cc” and “DOCSIS_Simulator.cc”. After including appropriate modules and defining source generator (homogeneous or heterogeneous) it starts simulation. During each time slot run, simulation time and slot count is incremented. Moreover, traffic generation, contention for bandwidth, data transmission, collision resolution and other MAC features are simulated. Statistics are gathered during all these activities. Finally, at the end of simulation, final statistics are stored in output results file.

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IMAGE EVALUATION TEST TARGET (QA-3)

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