國立交通大學

資訊科學研究所

碩士論文

混合式光纖同軸電纜上

密接式週期性上行傳輸協定的效能評估

Performance Evaluation of Pipelined Cyclic Upstream Protocol over Hybrid Fiber Coax

研究生:尹維銘

指導教授:林盈達

中華民國八十六年六月

混合式光纖同軸電纜上
密接式週期性上行傳輸協定的效能評估

Performance Evaluation of Pipelined Cyclic Upstream Protocol over Hybrid Fiber Coax

研 究 生 :尹維銘　　Student: Wei-Ming Yin
指導教授:林盈達　博士　　Advisor: Dr. Ying-Dar Lin

國立交通大學
資 訊 科 學 研 究 所

碩士論文

A Thesis
Submitted to Institute of Computer and Information Science
College of Electrical Engineering and Computer Science
National Chiao Tung University
in partial Fulfillment of the Requirements
for the Degree of
Master
in
Computer Science

June 1997
Hsinchu, Taiwan, Republic of China.

中華民國八十六年六月

混合式光纖同軸電纜上
密接式週期性上行傳輸協定的效能評估

研 究 生 :尹維銘　　指導教授:林盈達

國立交通大學資訊科學研究所

摘 要

有線電視網路的技術已經成熟，而普及率也相當的高，若在現有的有線電視網路上賦予雙向傳輸的功能，使得寬頻的互動式網路服務能延伸至家庭，改變資訊存取的形態，有助於國人對資訊的掌握及運用，增進國家競爭力。

在本篇論文中，我們提出一個適用於混合式光纖同軸電纜線的上層傳輸協定—PCUP。這個 PCUP 是應用管線模態於上行頻道中。這可以藉由兩種方式來達成:第一、用戶端定位，也就是測量用戶端和頭端的傳輸位移值;第二、傳輸排程，也就是在同一個週期中給予每個用戶端傳輸開始時間和傳輸時間長度。藉由計算傳輸開始時間和傳輸時間長度，這使得他們的傳送結果呈現密接狀。我們由模擬的結果來估計它的效能，包含：資料遺失率、傳輸量、存取延遲、存取延遲變異及公平性，並模擬 R-ALOHA 和 UniLINK 協定與之比較。另外，我們也對 PCUP 進行存取延遲的數學分析，並與模擬的結果進行比對。

論文的最後，我們根據 IEEE802.14 委員會到目前爲止所制定的草案，簡述用戶同步和碰撞解決等機制所採行的方法，並提出可進行研究的題目。

Performance Evaluation of Pipelined Cyclic Upstream Protocol over Hybrid Fiber Coax

Student: Wei-Ming Yin Advisor: Dr. Ying-Dar Lin

Institute of Computer and Information Science
National Chiao Tung University

Abstract

The cable TV network has matured and is adapted as residential access network. If the cable TV network is equipped with two-way communication functionality, it is feasible to extend interactive broadband services to the home. This information revolution will change the behavior of manipulation of information and promote our national competition capability.

In this work, we propose PCUP (Pipelined Cyclic Upstream Protocol) as the upstream MAC protocol for HFC access network. PCUP is designed with the intention of pipelining the upstream channel. This is achieved by station positioning and by transmission scheduling. By taking into account the propagation offsets and the transmission times, transmitted cells can appear back-to-back, i.e. pipelined, at the headend. We evaluate the behavior of our protocol through simulations to show the performance for loss ratio, throughput, delay, delay variance and fairness. Comparisons with R-ALOHA (Reservation Slotted ALOHA) and UniLINK are also made. We also examine the performance of access delay in mathematical model.

In the last of this work, common agreement of IEEE 802.14 working group is addressed. Final mechanisms for synchronization and collision resolution are detailed. We also pose some open technical issues within MAC operation for further research.

Acknowledgments

I greatly appreciates my parents for their supporting and encouraging during this work. I would also like to express my thanks to Dr. Chein-Hsun Wang at Mentor Data System Inc. (Hinschu Science-based Industrial Park, Taiwan) and Prof. Ying-Shih Way at Dept. of Communication Engineering, National Chiao Tung University (Hsinchu, Taiwan) for their thought-provoking discussion and suggestion during the course of this work.

Contents

1. Introduction ---- 1

2. Broadband Access Network Alternatives ---- 4

2.1 Broadband Access Network Issues ---- 4

2.1.1 Planning Challenges ---- 4

2.1.2 End-To-End Network Functionality ---- 5

2.1.3 Set-Top Terminals ---- 6

2.2 Architecture Alternatives ---- 6

2.2.1 Enhanced Copper, Digital Subscriber Line (DSL) Technologies 7

2.2.1.1 The Essence of xDSL ---- 7

2.2.1.2 xDSL Family ---- 7

2.2.1.3 The Evolution of xDSL ---- 10

2.2.2 Coaxial Cable Upgrade ---- 10

2.2.2.1 HFC Network Overview ---- 11

2.2.2.2 HFC Spectrum Allocation ---- 11

2.2.2.3 The Evolution of HFC ---- 12

2.2.3 Fiber Alternative ---- 13

2.2.3.1 Architecture Overview ---- 13

2.2.3.2 The Evolution of BPON ---- 14

2.3 Comparison of Access Alternatives ---- 14

2.4 Standard Associations ---- 16

2.4.1 DAVIC ---- 17

2.4.2 IEEE 802.14 Working Group ---- 17

3. Proposed MAC Protocols over HFC ---- 19

3.1 MAC Protocol Issues over HFC ---- 19

3.1.1 Synchronization and Positioning ---- 19

3.1.2 Collision Resolution ---- 20

3.1.2.1 Persistence Algorithms ---- 21

3.1.2.2 Tree Algorithm---------- 22
3.1.3 Bandwidth Allocation and Transmission Scheduling---------- 23
3.2 Widely-used MAC-layer Protocol : R-ALOHA ----------24
3.3 IEEE 802.14 Proposals ----------25
3.3.1 MAC Level Access Protocol (MLAP) ---------- 25
3.3.2 Adaptive Digital Access Protocol (ADAPt) ---------- 28
3.3.3 UniLINK ---------- 31
3.3.4 Framed Pipeline Polling (FPP) ---------- 33
3.4 Qualitative Comparison of MAC Protocols ----------34
4. Pipelined Cyclic Upstream Protocol ----------37
4.1 System Overall Description----------37
4.1.1 Overview ---------- 37
4.1.2 Data structures---------- 39
4.2 Membership control ----------41
4.2.1 On-line set construction ---------- 41
4.2.2 Channel usage control ---------- 42
4.3 Station positioning----------43
4.4 Transmission scheduling ----------45
4.5 Summary of PCUP ----------48
5. Simulation study ----------50
5.1 Network configuration----------50
5.2 Traffic models ----------50
5.3 Numerical results----------51
5.3.1 System throughput ---------- 51
5.3.2 Loss ratio ---------- 53
5.3.3 Access delay---------- 55
5.3.4 Cell delay variance (CDV) ---------- 57
5.3.5 Fairness---------- 58

6. Performance Evaluation ----------61

6.1 System Definition ----------61

6.2 Access Delay Analysis ----------61

6.3 Illustrative Results ----------63

6.4 Discussions ----------63

7. Common Agreement of IEEE 802.14 Working Group Committee ----------64

7.1 Physical Layer Specification ----------64

7.2 Medium Access Control Specification----------64

7.2.1 Station Addressing---------- 64

7.2.2 Channel Hierarchy ---------- 65

7.2.2.1 Upstream Channel Hierarchy ----------66

7.2.2.2 Downstream Channel Hierarchy----------66

7.2.3 Synchronization ---------- 67

7.2.4 Contention Resolution ---------- 68

7.3 MAC Operation ----------70

7.4 Open Technical Issues ----------72

8. Conclusions and Future Works ----------73

9. References ----------74

List of Figures

Figure 2-1. Full-service network functionality. 5
Figure 2-2. ADSL network diagram. 8
Figure 2-3. HFC network diagram. 11
Figure 2-4. HFC spectrum allocation. 12
Figure 2-5. BPON network diagram. 13
Figure 2-6. Evolutionary potential of access alternatives. 16
Figure 3-1. Delay adjustment. 20
Figure 3-2. Persistence algorithms. 21
Figure 3-3. Tree algorithm. 23
Figure 3-4. Reservation scheme of R-ALOHA protocol. 25
Figure 3-5. The phases of the MLAP philosophy. 26
Figure 3-6. The START-3 logical stack after a collision slot. 28
Figure 3-7. Upstream frame structure. 29
Figure 3-8. Downstream frame structure. 29
Figure 3-9. Upstream/Downstream timing relationship. 30
Figure 3-10. Dynamic allocation of bandwidth. 31
Figure 3-11. Timing relationship on upstream block sync interval. 32
Figure 3-12. Polling scheme. 34
Figure 4-1. State transition diagram of headend. 38
Figure 4-2. State transition diagram of station. 39
Figure 4-3. The frame structure of HE.invitation. 39
Figure 4-4. The frame structure of HE.balance. 39
Figure 4-5. The frame structure of HE.position. 39
Figure 4-6. The frame structure of HE.schedule. 40
Figure 4-7. Pseudo code for cycle membership control. 43
Figure 4-8. The tree-and-branch topology with data transmission. 44
Figure 4-9. The example timeline of pipelined data transmission. 44
Figure 4-10. Pseudo code of station positioning. 45
Figure 4-11. Look-ahead allocation. 48
Figure 4-12. Pseudo code of station operations. 49
Figure 4-13. Pseudo code of headend operations. 49

Figure 5-1. Throughput of PCUP, R-ALOHA and UniLINK under traffic model A. 52
Figure 5-2. Throughput of PCUP, R-ALOHA and UniLINK under traffic model B. 52
Figure 5-3. Throughput of PCUP, R-ALOHA and UniLINK under traffic model C. 52
Figure 5-4. Throughput under different channel capacities. 53
Figure 5-5. ABR traffic lost ratio under traffic model C. 54
Figure 5-6. CBR traffic lost ratio under traffic model C. 54
Figure 5-7. VBR traffic lost ratio under traffic model C. 55
Figure 5-8. Access delay of PCUP, R-ALOHA and UniLINK under traffic model A. 56
Figure 5-9. Access delay of PCUP under different cycle times. 57
Figure 5-10. ABR traffic cell delay variance(CDV) under traffic model C. 58
Figure 5-11. CBR traffic cell delay variance(CDV) under traffic model C. 58
Figure 5-12. VBR traffic cell delay variance(CDV) under traffic model C. 58
Figure 5-13. Access delay under traffic model C. 59
Figure 5-14. Successfully transmitted cells under traffic model C. 60
Figure 6-1. Timing relationship. 62
Figure 7-1. Calculating the round trip correction. 68
Figure 7-2. Request minislot allocation message. 69
Figure 7-3. Collision resolution state diagram. 70
Figure 7-4. Timeline of MAC operation. 71

List of Tables

Table 2-1. ADSL transport classes. 9

Table 2-2. Comparison of access alternatives. 15

Table 3-1. Features Comparison of proposed MAC protocols. 36

Table 3-1. Description of symbols. 40

Table 3-2. Request_Table. 41

Table 4-3. Station slot requests. 46

Table 7-1. Upstream channel hierarchy. 66

Table 7-2. Downstream channel hierarchy. 67

1. Introduction

We are witnessing an great demand from residential and business customers for access to the Internet, corporate Intranet, and various on-line information services in these past few years in Taiwan. We are also witnessing a rapid convergence of telecommunications and computing technologies. Such kind of ISP(Internet Service Provider) systems, whose data services delivery architecture are overlaid on a physical telephony and Internet platform, provide services including electronic commerce, home shopping, distance learning, multimedia conferencing, ... ,etc.. While more and more Internet applications such as WWW, containing rich graphical content, images, video and audio programs, software/document downloads, and so on, are popular, the immense bandwidth requirement makes data services access result in *world-wild-wait* syndrome. The Internet users have to routinely wait tens of seconds to several minutes to browse Web document or download multimedia files over the Internet.

To satisfy the requirements of these non-text-oriented applications, we demand a high-speed data services delivery infrastructure. Currently, there are three possible alternatives that can be used to bring high-speed connectivity to end users: 1) *Digital telephone lines*, 2) *Cable TV systems*, 3) *Aerial transmission systems*. In order to provide sophisticated interactive broadband services, upstream channels, or return paths, are required for transmission from customer sites.

Of these three alternatives, the aerial transmission systems can currently be used only in a hybrid mode where the return path is based on the use of voice-grade modem, that is, applying PSTN(Public Switch Telephony Network)

link to transport upstream traffic from the subscriber to the service provider. Hence, this solution can only be temporary due to the limitations of the return path and added complexity in system operation. The digital telephone service has been evolving for over a decade. The most widely available offering is the ISDN(Integrated Services Digital Network) basic rate services that can provide up to 128 Kbps over currently deployed unshielded twisted pair (UTP) copper cabling. But 128Kbps is no longer sufficient for a full range of broadband services. Telephony operators are also testing new asymmetric communication technologies that will allow for hundreds of kilobits per second transmission speed on the return path, and several megabits per seconds transmission speed on the downstream channel. However this technology has not yet sufficiently matured and the equipment is still too expensive to be affordable to residential customers.

On the other hand, CATV plants can provide unsurpassed aggregate bandwidth about 1GHz to support high-speed data transmissions. Hence, for the past few years, most cable companies have upgraded their infrastructure to support two-way asymmetric communications. This two-way communication cable system will provide speeds of several tens of megabits per second on the downstream and several megabits per second on the upstream. With such high channel capacity, CATV systems can provide a full range of interactive broadband services to end users in the foreseeable future. The key technical issue of this residential access network is the multiple access protocol over upstream channels. In other words, the communication standard will be required to make this information revolution effective. This is also the major work of IEEE 802.14 committee in next few years.

In this work, we proposed a ***Media Access Control (MAC)*** protocol

PCUP(Pipelined Cyclic Upstream Protocol) which is designed with the intention of pipelining the upstream channel. This is achieved by proper station positioning, which measures the station propagation offset from the headend, and transmission scheduling, which assigns each station the transmission starting time and duration in a cycle. By taking into account the propagation offsets and the transmission times, transmitted cells can appear back-to-back, i.e. pipelined, at the headend. Since only the active stations are scheduled to transmit in a cycle, a membership control mechanism, a contention-based tree walk algorithm, is executed periodically to allow the stations to join or leave.

In chapter 2, we make a survey of the broadband data services delivery architectures and comparison of these alternatives. There are open technical issues in provisioning broadband data services over residential access network addressed in chapter 3. Qualitative analysis over some selected protocols submitted to IEEE 802.14 committee are also made in this chapter. The protocol, PCUP, is presented in chapter 4. We simulate the behavior of PCUP, based on the criteria submitted to IEEE 802.14 Working Group, and compare it with R-ALOHA (Reservation Slotted ALOHA) and UniLINK in chapter 5. After qualitative and quantitative analysis of PCUP, we make mathematical analysis of this protocol by queuing model in chapter 6. Cable modem trial based on CATV environment is pictured in chapter 7. Final conclusions and pointers for future works are given at the end of this work.

2. Broadband Access Network Alternatives

2.1 Broadband Access Network Issues

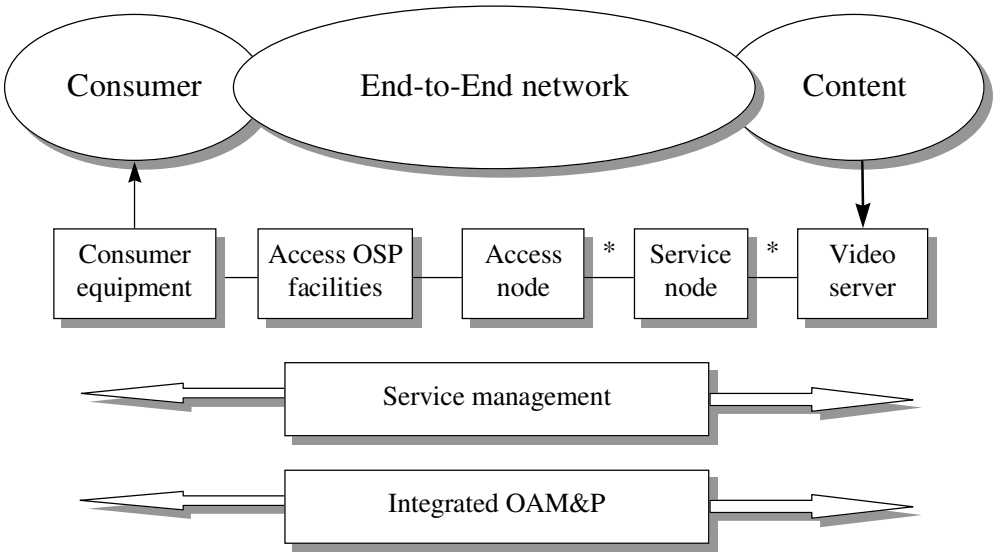
2.1.1 Planning Challenges

Planning a broadband services network is challenging in two regards - evolution in services and technologies and construction lag. Due to the changing behavior of customers and unpredictable market trend in a multi-provider environment, the predictability of new services over such a planning network is highly uncertain. Thus, a critical aspect of broadband network planning is for flexibility to accommodate changing services and business needs. It should also be noted that network capacities and costs will change over time and will enable or constrain service evolution. For instance, digital VOD (Video-On-Demand) may initially be less popular than analog broadcast video since the need for expensive set-top equipment, modulation, and video server architecture technologies. This will change in the future with cost reductions while demand increases, improvements in video compression, and advances in the underlying technologies.

Another challenge in broadband network planning is the long construction lag. Obtaining the capital, manufacturing the network components, marshaling the construction and provisioning capacity to provide full-services access network to a 80 miles area will take a long time. As technology improves and services mature or fail, the network design under construction at any point in time will change. There is a strong operational need to maintain backward compatibility, while continuing to support new services as they evolve.

2.1.2 End-To-End Network Functionality

Figure 2-1 provides an end-to-end functional view of a full-service network that conveys programming contents to information consumers. Content is stored by information providers in video servers. Consumer equipment terminates individual services and presents content to consumers. Access OSP(Outside Plant) facilities provide the so-called "last mile" physical link to individual consumer premises. It covers all active and passive devices as well as all cabling. The access node manages all access OSP facilities within a defined area and provides appropriate format and transmission conversion to meet internal network interfaces for both communications and video servers. It is typically located within the Central Office (CO) or headend (HE). The service node provides switching and processing functionality that connects a consumer to the server. Note that service node and video servers may be collocated with the access node.



■ **Figure 2-1.** Full-service network functionality.

Two additional end-to-end blocks are shown in Figure 2-1. Service

management provides the gateway via which a consumer selects information providers, manages service options and navigates among program choices. Integrated OAM&P (Operations, Administration, Maintenance and Provisioning) refers to all the operational capabilities designed into smart broadband network elements and element managers that enable a network provider to operate a full-service network with high efficiency and minimal human intervention.

2.1.3 Set-Top Terminals

A key cost issue within the implementation of the full-service broadband network is the set-top terminal. It is a part of consumer's premises and is expected to provide the interactive interface for many broadband services. It would certainly include functionality for access transmission termination and decompression for each of the simultaneous digital video channels, as well as access security functions to support billing and eliminate theft of services. It may also include:

- Functionality for onscreen navigation and selection of services.
- Functionality for application download from network for provisioning, configuring, and maintaining services.
- Random access memory for real-time operation of the system and processing of some applications as video games.
- Ports or plug-in slots for providing access to peripheral devices like printers, CD-ROM drivers, and high-speed data modems.

2.2 Architecture Alternatives

There have been a wide range of architectures proposed for upgrading the physical layer of the access network to broadband. At present no single technology or network architecture seems the obvious choice. In this work, we consider three wired alternatives: twisted copper pair, coaxial cable, and optical fiber. The broadband radio and satellite-base alternatives are not studied here.

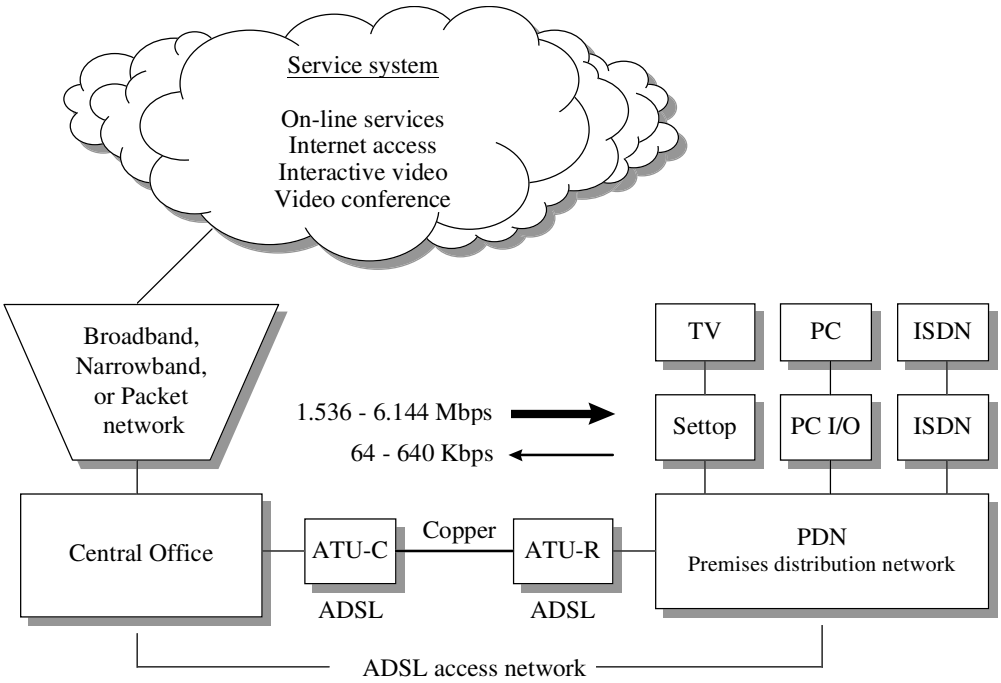
2.2.1 Enhanced Copper, Digital Subscriber Line (DSL) Technologies

2.2.1.1 The Essence of xDSL

For decades, the audio spectrum consists of only the 4kHz of total spectra available on a typical pair of telephone wire. However, the entire spectra of transmittable frequency over copper wire is typically in the area of 1MHz. These available frequencies have not been used previously due to the difficulties they cause for normal transmission of voice traffic. Transmission above 4 kHz over a pair of copper wires in a binder tend to disrupt plain old telephone service (POTS) by introducing unacceptable levels of near-end crosstalk to other wire pairs in the same binder. Nowadays, with the advancement of lower-cost and more powerful digital signal processing (DSP) chips, these available frequencies highly attract human's attention. xDSL technologies employ highly sophisticated techniques that limit neat-end crosstalk and therefore greatly expand the bandwidth potential over a single pair of copper pair. They also permit POTS service to operate simultaneously on the same wire pair upon which xDSL transmission takes place.

2.2.1.2 xDSL Family

While there are many flavors of xDSL technology, ***Asymmetric DSL (ADSL)*** perhaps holds the greatest potential for mass deployment. Figure 2-2 shows the ADSL network model.



■ **Figure 2-2.** ADSL network diagram.

.At present, ADSL has three candidate modulation technologies, or line codes, making their way to marketplace. They are discrete multitone (DMT) modulation, quadrature amplitude modulation (QAM) and carrierless amplitude-phase (CAP) modulation. ADSL achieves its asymmetrical bandwidth structure by dividing the local loop into four classes of channels: higher-bandwidth simplex (unidirectional) channels, lower-bandwidth duplex (bidirectional) channels, a duplex control channel and a POTS channel, which occupied the lowest 4 kHz of spectra. Transmission occurring on either the simplex or duplex channels does not affect the POTS channel. This ability to simultaneously provide POTS service alongside broadband data and/or video services within the same wire pair is one of ADSL's primary advantages relative to other access technologies, such as ISDN. Table 2-1 describes seven ADSL transport classes standardized by ANSI. Classes 1, 2, 3 and 4 are based on multiples of T-1 (1536 kbps) downstream bandwidth and classes 2M1, 2M2 and 2M3 are based on multiples of E-1 (2048 kbps) downstream bandwidth. The

serving area for these transmission rates ranges from 12000 ft to 18000 ft.

Transport class	1	2	3	4	2M1	2M2	2M3
downstream simplex channels	6144	4608	3072	1536	6144	4096	2048
upstream duplex channels	640	608	608	176	640	608	176
control channel	64	64	64	16	64	64	16
POTS channel	64	64	64	64	64	64	64

■ **Table 2-1.** ADSL transport classes. Bandwidth unit is kbps.

Rate-Adaptive DSL (RADSL) technology is a subset of ADSL that automatically adjust line speed according to a series of initial tests that determine the maximum speed possible on a particular line. ***Very-High Rate DSL (VDSL)*** is also essentially the same as ADSL. However, VDSL is design for much higher transmission rate (up to 30 to 51 Mbps) than ADSL over extremely short distances (500 to 1000 ft). Because of this high transmission rate and severe distance limitation, VDSL could be used in conjunction with fiber to the curb (FTTC) described below to support residential broadband applications.

Symmetric DSL (SDSL), as expected, provides the same amount of bandwidth upstream and downstream. Such system may operate at 384kbps, 768kbps, 1.536Mbps(T-1) or 2.048Mbps(E-1). For this reason, SDSL is not considered as a contender to provide broadband services to the residential network. This technology is mostly used as the underlying transmission scheme over the wide area network. Accordingly, transporting frame relay traffic over a SDSL link is cost effective. SDSL's symmetric transmission scheme is also optimized for some isochronous applications such as video conferencing, which

has the same bandwidth requirement downstream as upstream.

The last xDSL access technology, ***High-Bit-Rate DSL (HDSL)***, is the most widely deployed xDSL technology and has been commercially available for a number of years. Unlike the other xDSL technologies, HDSL uses two pairs of copper cable and does not carry POTS. Most HDSL implementations provide 1.536Mbps or 2.048Mbps of symmetric bandwidth up to 12000 ft from the central office. Nowadays, HDSL needs to develop and expand its distance and bandwidth capacity. Otherwise, SDSL, requiring only a single copper pair for transmission, will emerge as the superior solution.

2.2.1.3 The Evolution of xDSL

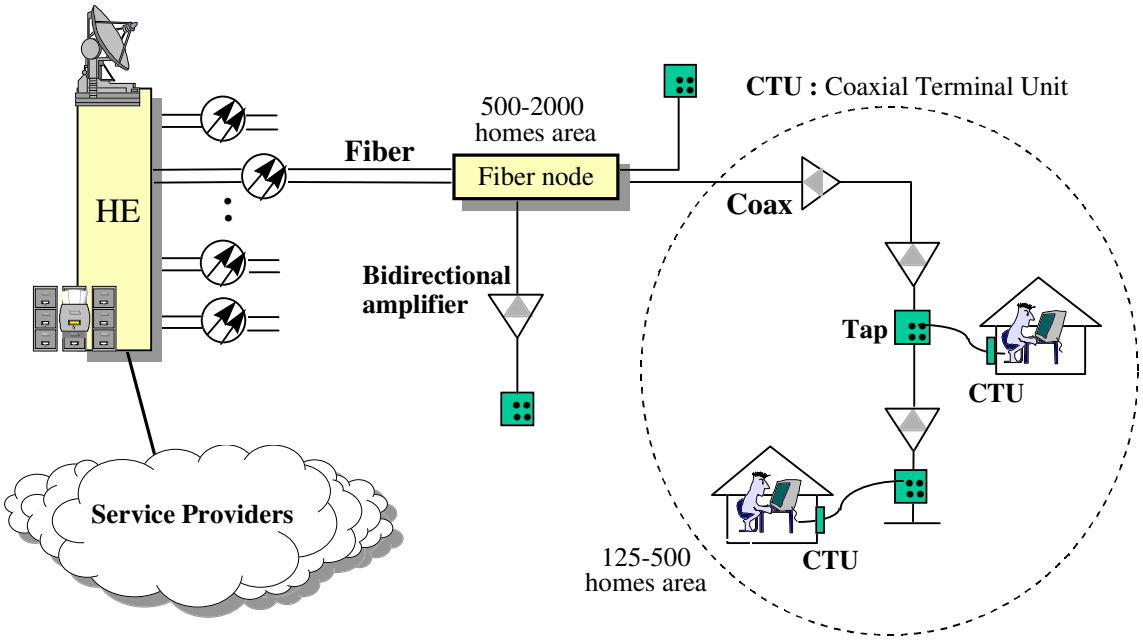
ANSI, the European Telecommunications Standards Institute (ETSI), and the International Telecommunications Union - Telecommunications Standardization Sector (ITU-T) are actively involved in creating standards for xDSL. Additionally, since ADSL and VDSL, in particular, provide a platform for new residential broadband services, there are two other organizations draft the specification of ADSL and VDSL. These organizations include the ATM Forum, the ADSL Forum, the Telecommunications Industry Association (TIA), and the Digital Audio Visual Council (DAVIC). As the drafting of standards progresses, xDSL technologies continue to advance rapidly. Higher performance/price will lead these technologies to succeed for a decade.

2.2.2 Coaxial Cable Upgrade

The ***Hybrid Fiber Coax (HFC)*** technology allows provision of upstream channel capacity in the coaxial cable distribution network. That is, splitting the coaxial cable network into smaller coaxial segments in order to achieve the required upstream channel capacity.

2.2.2.1 HFC Network Overview

Figure 2-3 represents a HFC system. 500 to 2000 subscribers are served by a fiber that comes from the headend to a fiber node. These signals distribute to homes by electrical signal within the serving area of a fiber node via an amplified tree-and-branch feeder cables. Each station can not directly listen to the upstream transmissions from other stations; hence, they are incapable of detecting collisions and ultimately coordinating their transmission by themselves. With multiple access technology, upstream channel lets all subscribers within a branch share the available reverse bandwidth and a single fiber carries the signal back to the headend.

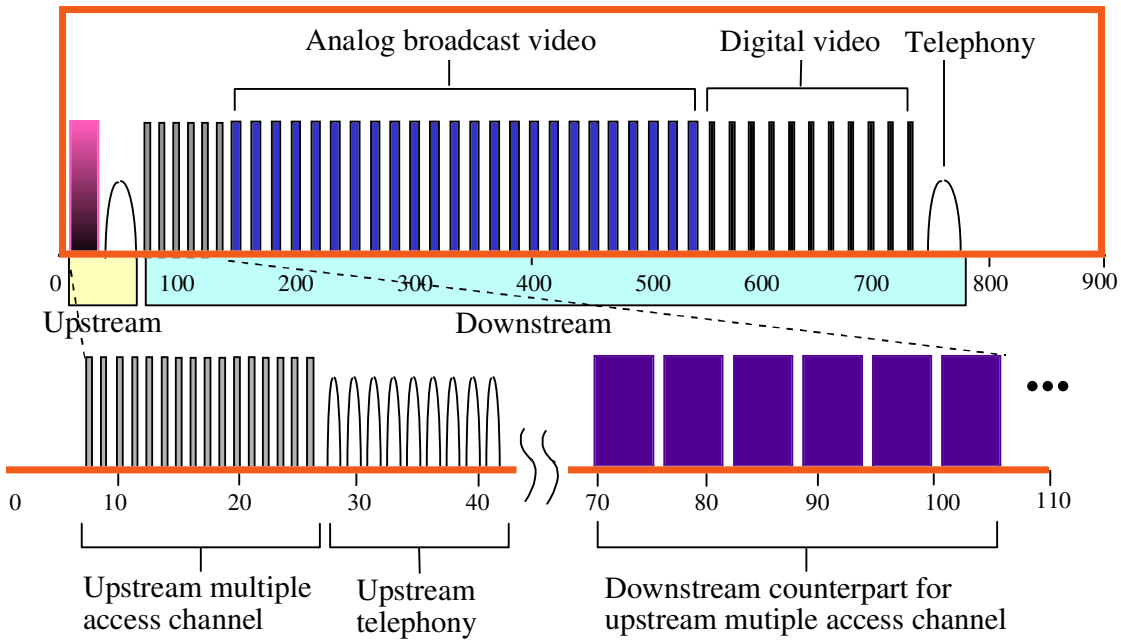


■ **Figure 2-3.** HFC network diagram.

2.2.2.2 HFC Spectrum Allocation

The frequency spectrum for consumers to use is given in Figure 2-4. Assume that total bandwidth of at least 800 MHz is available on all the coaxial cable links. A 400 MHz band, from 150 MHz to 550 MHz, may be used to carry

conventional analog broadcasting programs, while digital downstream services such as *video on demand (VOD)* programs are transmitted in the range from 550 MHz to 750 MHz. A 18.5 MHz band from 8 to 26.5 MHz can be divided into 17 upstream digital channels, each of which can be 1.544 Mbps. These upstream channels are called "*multi-access channels*" and used to carry signaling and other bursty data. A larger bandwidth in downstream, 70 to 130 MHz, is used to mirror those upstream *multi-access channels*. Other constant bit rate services or delay sensitive applications, such as voice and video telephony, use 27 MHz to 54 MHz in upstream and 750 MHz to 800 MHz in downstream.



■ **Figure 2-4.** HFC spectrum allocation.

2.2.2.3 The Evolution of HFC

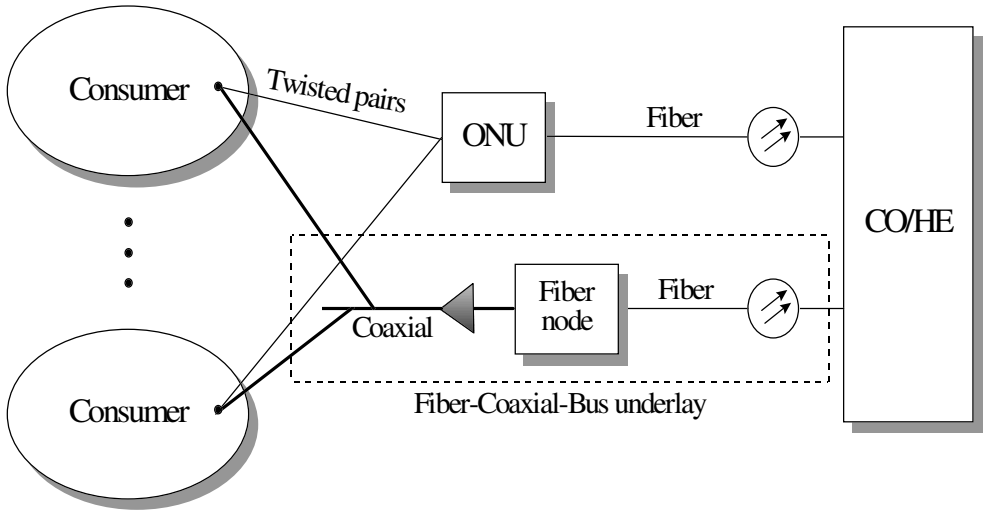
IEEE 802.14 project has worked for drafting the standard for the use of HFC cable plant in supporting both traditional and new services during past few years. ANSI, ATM Forum, Digital Audio Visual Council (DAVIC) and Multimedia Network Cable Service (MNCS) are actively involved in creating this standard. Many proposals had submitted to the working group, and the final IEEE 802.14

standard will be accomplished in June 1998. Nowadays, the first transmission rule, collision resolution and frame structure of MAC layer are mostly defined. Parameters such as 64QAM, QPSK, CRC and scramble of PHY layer are also defined. It is expected that the rapid progress will be made in this field for next few years.

2.2.3 Fiber Alternative

2.2.3.1 Architecture Overview

This kind of system which presents fiber in the loop (FITL) refers to ***broadband passive optical network (BPON)***. Figure 2-5 illustrates a practical BPON architecture.



■ **Figure 2-5.** BPON network diagram.

BPON systems typically offer 622Mb/s or 155Mb/s downstream capability and 155Mb/s upstream capacity. The access is shared between 16 or 32 optical network units (ONU) with statistical multiplexing capacity. In an idealized view, all traffic except analog broadcast video is carried digitally over fiber facilities from the central office or headend to ONU located deep in the plant. Since it is costly to equip a dedicated receiver at the consumer site to

catch digitized broadcast analog TV signals on fiber, a practical BPON system are usually constructed with a *Fiber-Coaxial-Bus* underlay carrying analog cable TV channels. According to residential network conditions, ONU might be located in the plant as deeper as necessary. Thus, several architectures like ***Fiber To The Building (FTTB)***, ***Fiber To The Curb (FTTC)***, and ***Fiber To The Home (FTTH)*** are proposed.

2.2.3.2 The Evolution of BPON

FTTH technology provides the direct access to virtually unlimited raw bandwidth to residential consumers. This is the ultimate in wireline full-service network architecture. It is secure and robust, but may not be very cost effective for massive deployment because the infrastructure does not exist yet. In addition, problems such as network management and service interoperability need proper resolution.

2.3 Comparison of Access Alternatives

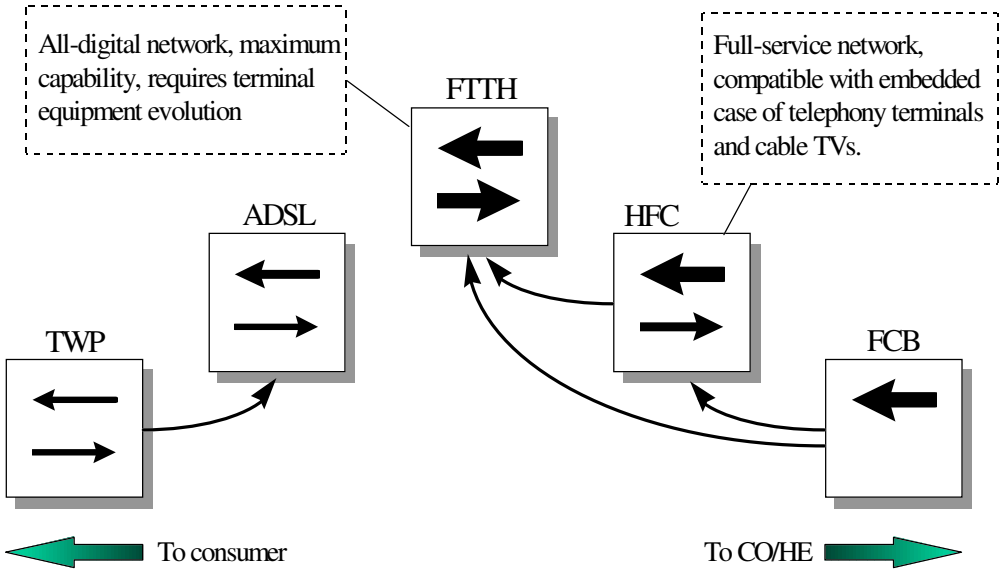
After describing commonly used access alternatives except for wireless technologies, comparison of these alternatives is summarized in table 2-2 in terms of their network capacity and service support. TWP refers to twisted wire pair that currently provides POTS services. FCB refers to fiber coaxial bus that currently provides traditional TV channels. Note that the terms narrowband (NB), wideband (WB) and broadband (BB) are traditionally associated with voice telephony (Nx64 kbps), high speed data (Nx1.5 Mbps) and entertainment video, respectively, with the NB to WB boundary at 1.5Mbps and the WB to BB boundary at 45Mbps. BB/WB, for example, implies downstream bandwidth is broadband and upstream bandwidth is wideband.

Access	TWP	FCB	ADSL	HFC	FTTH

alternative					
Network capacity	2-way Symmetric NB/NB Switch	1-way Asymmetric BB/- Non-switch	2-way Asymmetric WB/NB Switch	2-way Asymmetric BB/WB Switch	2-way Symmetric BB/BB Switch
Services supported	Telephony	Analog TV	Telephony Digital VOD E-commerce	Telephony Analog TV Digital VOD E-commerce Video-phone	Telephony * Analog TV Digital VOD E-commerce Video-phone

■ **Table 2-2.** Comparison of access alternatives.

The last column in table 2-2 reflects a ideal consumer environment, expected to be all digital and to require broadband capacity even in the upstream direction. Star mark means that the presentation of analog TV on fiber in costly due to expensive receiver equipment on FTTH architecture. However, HDTV programs which may be popular in next century will be fit within this environment. HFC represents an upgrade for existing FCB network by providing digital downstream capacity for VOD channels and upstream bandwidth managing digital VOD services. Figure 2-6 illustrates the evolutionary potential of the alternatives based on the information developed in table 2-2.



■ **Figure 2-6.** Evolutionary potential of access alternatives.

Since neither the consumer environment nor technology investment are present, ADSL technology really does not deserve an evolutionary option toward full-service capacity. Take cost and technology maturation into consideration, industry attention currently focused on HFC alternatives that including traditional analog video underlay. The critical deciding factors are near-term full-service capability and compatibility with the current consumer equipment. Following chapters will characterize the MAC layer protocol based on HFC access network.

2.4 Standard Associations

Several standard associations such as DAVIC , IEEE 802.14, National Cable Television Associations, and Interactive Multimedia Association were formed to seek the total solutions for interactive multimedia services over backbone and community networks. We now give a brief discussion of DAVIC and IEEE 802.14 activities.

2.4.1 DAVIC

DAVIC (Digital Audio Visual Interoperability Council) is a non-profit association, targeted to achieve the success of emerging digital audio-visual applications and services. All the technical work is carried out by TC (Technical Committees) under the supervision of management committees. There are six TCs: applications, information representation, sub-systems, physical layer, system integration and security. DAVIC 1.0 specifications were issued and have been reduced to just one solution — either by consensus or, if necessary, by a process of voting. There are some important parts in DAVIC specifications 1.0:

- Functionality supported by DAVIC 1.0 and its system reference models.
- Architecture and API of server, delivery system, and STU.
- Layer-protocols and physical interfaces.
- Information representation and protocols format.
- Access control scheme.
- Reference points and interfaces.

The specification starts with overall scenario including supported functionality, requirements, and system model. Following the architectures/APIs of each component and protocols of each layer, security and some miscellaneous issues are in the remaining parts. The DAVIC specification is now far from complete and further work is on-going.

2.4.2 IEEE 802.14 Working Group

IEEE 802.14 takes the responsibility for the standardization of digital convergence, focusing on broadband information stored and delivered within residential access network. Since 1994, IEEE project 802.14 has devoted to provide standards for the use of the HFC cable plant in supporting both traditional and new services. These services include:

- CBR (Constant Bit Rate).
- VBR (Variable Bit Rate).
- ABR (Available Bit Rate).

CBR typically applies to voice and video, is scheduled to transmit in a fairly constant interval time. VBR usually supports compressed video, which provides bounded delay. ABR is the lowest-priority service that is suitable for data transfer, and its delay is non-deterministic.

This list of services looks familiar with services provided by ATM, but the main difference is that the cable is shared. It is more difficult to meet the requirement of CBR, VBR, and ABR traffic with shared medium because of the problems of fairness, bandwidth reservation and bounded delay due to multiple access. The solution of MAC-layer protocol may include a combination of contention, reservation, polling, and slotted collision schemes. The evaluation criteria of IEEE 802.14 are :

- Topology
- Fairness vs. optimality
- Traffic control
- Asymmetric and symmetric support
- Latency of services
- CBR, VBR, and ABR service support
- Bandwidth efficiency
- ATM support
- Simplicity and economy of operation

3. Proposed MAC Protocols over HFC

3.1 MAC Protocol Issues over HFC

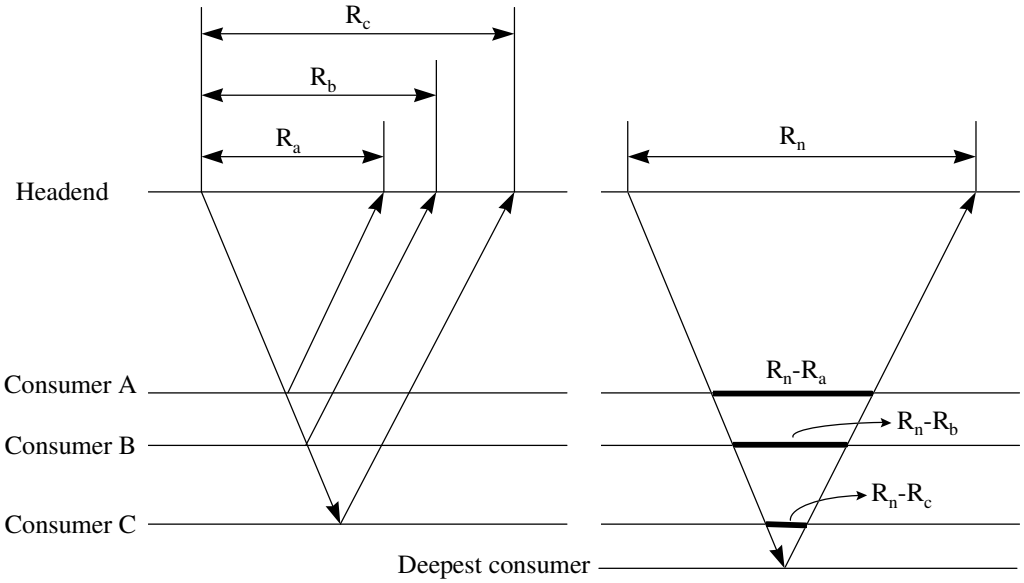
Due to the tree-and-branch architecture of HFC access network, synchronization process among different consumers becomes more complicated than other network topologies like bus and ring. There has been many efforts devoted to neutralize the propagation delay between consumer and headend and will be illustrated in following sections. It is pointed out in section 2.2.2.1 that one can only listen on downstream channels and transmit over upstream channels. Hence, they are incapable to detect collisions and coordinate their transmission by themselves. Thus, collision resolution plays an important role in a HFC MAC protocol. To provide a full-service environment that accomplishes electronic-shopping, video-on-demand, .. etc., at home, isochronous bandwidth is necessary duo to real-time and delay sensitive applications. There rises the issue of bandwidth allocation and transmission scheduling which are highly associated with quality of service (QoS). Issues presented above will be detailed in the following section.

3.1.1 Synchronization and Positioning

In order to neutralize the propagation delay between consumer and headend for all consumers, synchronizing process is necessary. Among all proposals submitted to IEEE 802.14 committee, the general way to compensate the network delays is as follows. A consumer needs two information to line cells up that precisely in their assigned slots:

- a global timing reference
- knowledge of its own round trip delay

Once obtaining these information, delay adjustment can be achieved as described in Figure 3-1. R_n is maximum network round trip delay and R_a, R_b, R_c are round trip delays of consumer A, B, C, respectively. Upon receiving a global timing reference signal, or cycle beginning preamble, each consumer waits R_n-R_a, R_n-R_b, R_n-R_c, respectively, and transmits its data. The headend receives data from the consumers, Rn after sending the timing reference signal. Thus, delays of different consumers can be absorbed and all consumers may be viewed as located at the same distance.



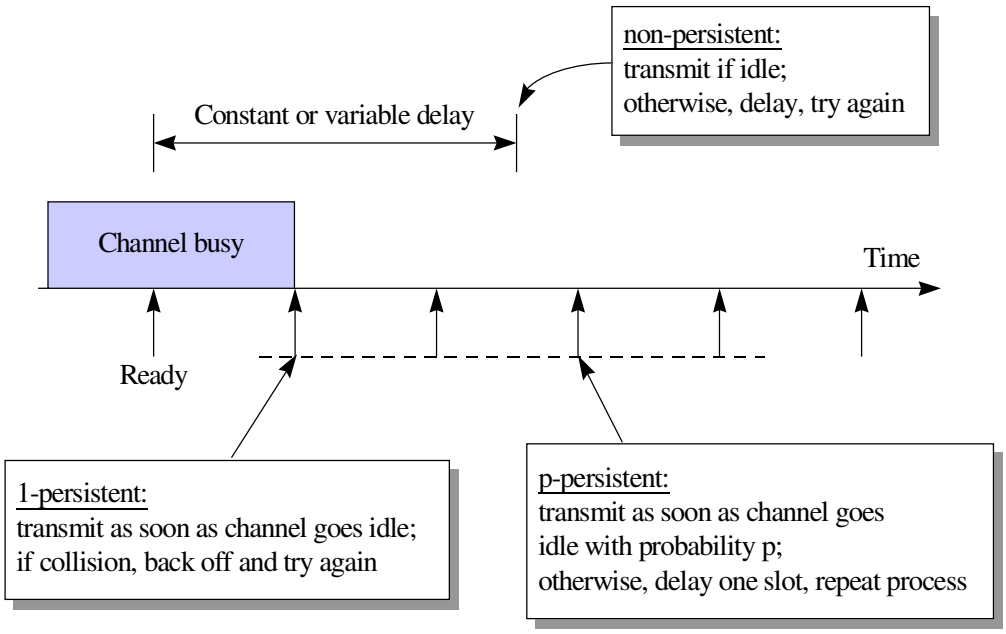
■ **Figure 3-1.** Delay adjustment.

3.1.2 Collision Resolution

Since consumers can't detect collision by themselves, collision resolution of HFC MAC protocol becomes more complicated than that of traditional LAN MAC protocols like CSMA/CD. Two kinds of collision resolution algorithms will be addressed as follows.

3.1.2.1 Persistence Algorithms

The listen before talk is widely used technology among local area network MAC protocols. A station wishing to transmit first listens to the medium to determine if another transmission is in progress. If the medium is in use, the station backs off some period of time and tries again. Three approaches are depicted in Figure 3-2.



■ **Figure 3-2.** Persistence algorithms.

One algorithm is non-persistent. A station wishing to transmit listens to the medium and obey the following rules:

1. If the medium is idle, transmit.
2. If the medium is busy, wait an amount of time drawn from a probability distribution (the retransmission delay) and repeat step 1.

The use of random retransmission times reduces the probability of collisions. The drawback is that even if several stations have a packet to send, there is likely to be some wasted idle time following a prior transmission. To

avoid channel idle time, the 1-persistent algorithm can be used. A station wishing to transmit listens to the medium and obeys the following rules:

1. If the medium is idle, transmit.
2. If the medium is busy, continue to listen until the channel is sensed idle, then transmit immediately.
3. If there is a collision (determined by a lack of acknowledgment), wait a random amount of time and repeat step 1.

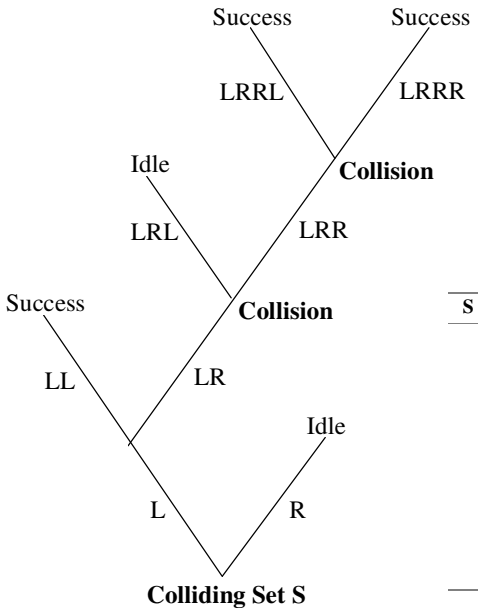
Whereas non-persistent stations are deferential, 1-persistent stations are selfish. Of two or more stations are waiting to transmit, a collision is guaranteed. A compromise that attempts to reduce collision, like non-persistent, and reduce idle time, like 1-persistent, is p-persistent. The rules are :

1. If the medium is idle, transmit with probability p, and delay one time unit with probability (1-p). The time unit is typically equal to the maximum propagation delay.
2. If the medium id busy, continue to listen until the channel is isle and repeat step 1.
3. If transmission is delayed one time unit, repeat step 1.

3.1.2.2 Tree Algorithm

The idea of tree algorithms is splitting the set of colliding nodes into subsets, one of which transmits in the next slot. If the collision is not resolved, then a further splitting into subsets takes place. More detail, see Figure 3-3, when a collision occurs, say in the kth slot, all nodes not involved in the collision go into a waiting mode, and all those involved in the collision split into two subsets (e.g., by each flipping a coin). The first subset transmits in slot k+1, and if that slot is idle or successful, the second subset transmits in slot k+2.

Alternatively, if another collision occurs in slots k+1, the first of the two subsets splits again, and the second subset waits for the resolution of that collision. Feedback is the receiver report for 0 packet, 1 packet, or more than one packet (e for error) were transmitted in that slot.



Slot	Xmit Set	Waiting Sets	Feedback
1	S	-	e
2	L	R	e
3	LL	LR, R	1
4	LR	R	e
5	LRL	LRR, R	0
6	LRR	R	e
7	LRRL	LRRR, R	1
8	LRRR	R	1
9	R	-	0

■ **Figure 3-3.** Tree algorithm.

3.1.3 Bandwidth Allocation and Transmission Scheduling

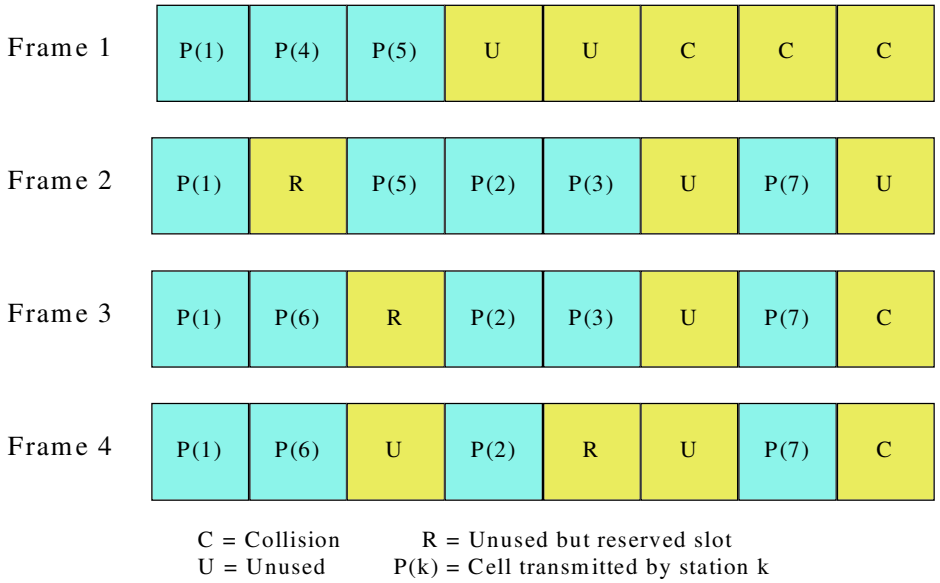
Interactive or conversational applications set a bound on end-to-end delay. Video on demand programs require acceptable delay jitters. To satisfy these requirements, a HFC MAC protocol must supply isochronous and reservation bandwidth. It also supplies contention bandwidth to reduce the access delay while traffic load is light. Thus, the ideal protocol should support a combination of isochronous, reservation and contention bandwidth. Transmission scheduling is highly associated with whether the protocol is fair or not. Although some bandwidth allocation features may lead some stations to starvation, transmission scheduling still dominates the fairness of bandwidth usage. First come first serve (FCFS) scheduling discipline may cause some

stations with posterior request messages fail to burst their data in acceptable delay duo to stations with prior request messages pumped large granted data. From another point of view, if we gather all request messages within this cycle and then make scheduling according to their priorities. This scheme seems to be fair and work reasonably well. But one may not burst its data within this cycle while FCFS scheduling may. In designing a MAC protocol, the compromise should be reached to achieve better performance.

3.2 Widely-used MAC-layer Protocol : R-ALOHA

R-ALOHA (Reservation slotted ALOHA) was originally proposed to improve the throughput of a satellite channel beyond that of slotted ALOHA. In this scheme, the broadcast channel is slotted, and the slots are organized into frames. Each time slot is long enough for the transmission of a cell. A time slot may be (1) idle, which means that it is empty, (2) collision, which means that two or more cells are transmitted into it and thus none could be received correctly, (3) success, which means that exactly one cell is transmitted into it and is successfully received.

The network operates without any central control, but requires each station to obey the same set of rules depending upon what happened in the previous frame. Successful transmission in a slot serves as a *reservation* for the corresponding slot in the next frame. By repeated use of that slot position, a station can transmit a long stream of data. A station wishing to transmit monitors the slots in the current frame. Any unused slot is available in the next frame. The station may contend for that slot using slotted ALOHA protocol. The reservation scheme is illustrated in Figure 3-4.



■ **Figure 3-4.** Reservation scheme of R-ALOHA protocol.

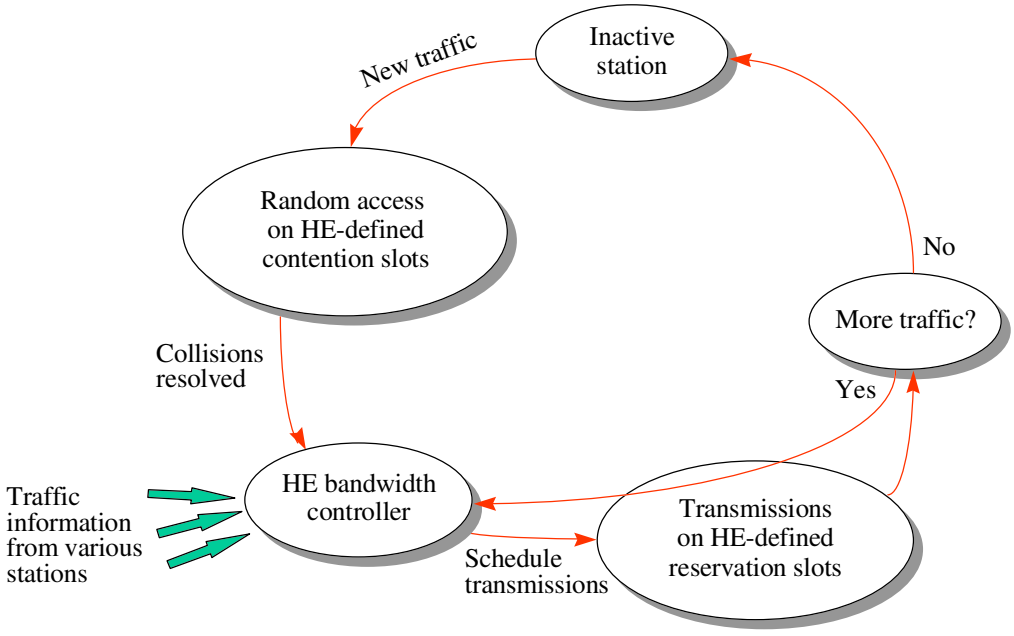
Some observations may be made. First, this protocol allows a dynamic mixture of stream and bursty traffic. If the average message stream is long, the system behaves like a fixed-assignment TDMA scheme. If most of the traffic is bursty, the performance may be degraded to S-ALOHA. In fact, performance could be even worse than S-ALOHA if most messages are one slot in length because the reserved but unused slots in the next frame are wasted. Second, there is a basic fairness problem since a station can capture a sequence of slots for an indefinite time; if many stations are active with long messages, average access delay to capture a slot would be considerable and starvation may happen.

3.3 IEEE 802.14 Proposals

3.3.1 MAC Level Access Protocol (MLAP)

Described here is the MLAP protocol proposed by IBM corporation. The basic philosophy behind MLAP is summarized in Figure 3-5. Inactive station

(phase 1) need not do anything. When new traffic is generated in a station, the station attempts to notify the headend of its new traffic through random access mechanism (phase 2). For this reason, the headend periodically notifies all the stations, through transmissions on the downstream channel, of time intervals during which contention-based transmissions can occur on an upstream channel. When collisions are successfully resolved and bandwidth request reaches the headend, a bandwidth controller at headend schedules next frame's transmission for each station (phase 3). In order for the network to support integrated services, the traffic scheduling will be guided by QoS constraints. Once again, stations are notified on the downstream of time intervals during which prescheduled reservation-based transmissions can occurs (phase 4). Finally, if an active station generates additional traffic (phase 5-yes), it can use reservation scheme to convey to the headend information regarding the additional traffic.



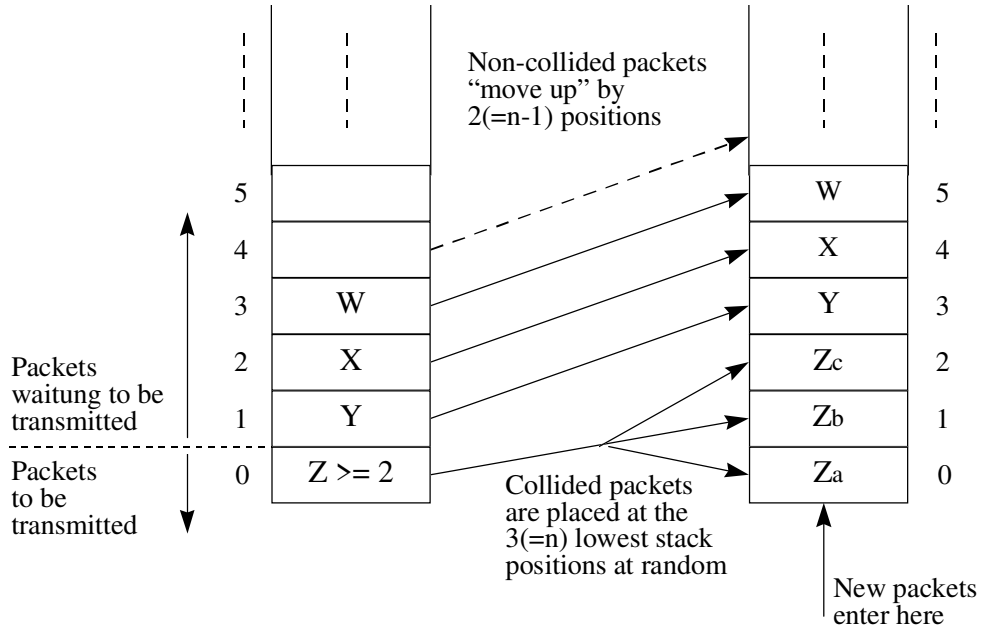
■ **Figure 3-5.** The phases of the MLAP philosophy.

MLAP is supplemented by a MAC-level management protocol (MLMP),

which is designed to operate independent of the MLAP on a full-duplex, shared-media, headend-controlled network. Major function of MLMP is plug-and-play join process used to attach a station to the network after power-on. The join process consists of invitation-seeking process, ranging process and station configuration process. For more details, make a reference to [??]. After join process, synchronization among different stations within the same HFC network may be achieved. How a station to convey to the headend information about its bandwidth requests? MLAP uses the n-ary STAck ResoluTion (START-n) algorithm as its collision resolution algorithm. This algorithm is implemented via a simple counter that is initialized to be 0 whenever the station has new traffic to transmit. Suppose a station has already made its first transmission; it performs the following algorithm:

```
if (collision)
    if (station transmitted)
        counter = random[0, . . . , n-1];
    else
        counter = counter + n-1;
elseif (no collision)
    if (station transmitted)
        done;
    else
        counter = counter -1 ;
endif
if (counter equals zero)
    transmit in the next slot;
```

According to above algorithm, following a collision the collided stations randomly set their counters between 0 and n-1, while the noncollided stations "make room" for the collided packets by increasing their counters by n-1. Following a noncollision slot, all active station decrement their counter by 1. Figure 3-6 shows how START-3 algorithm operates. X, Y, Z, ... denote the collection of packets in the corresponding stack levels. Following a noncollision slot, all packets go down one stack level.

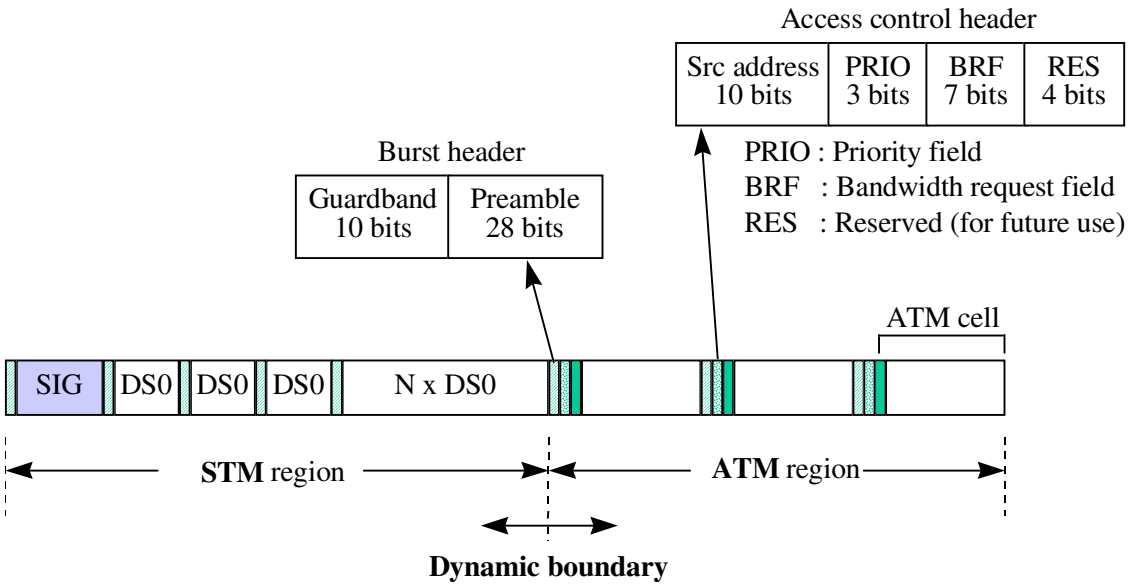


■ **Figure 3-6.** The START-3 logical stack after a collision slot.

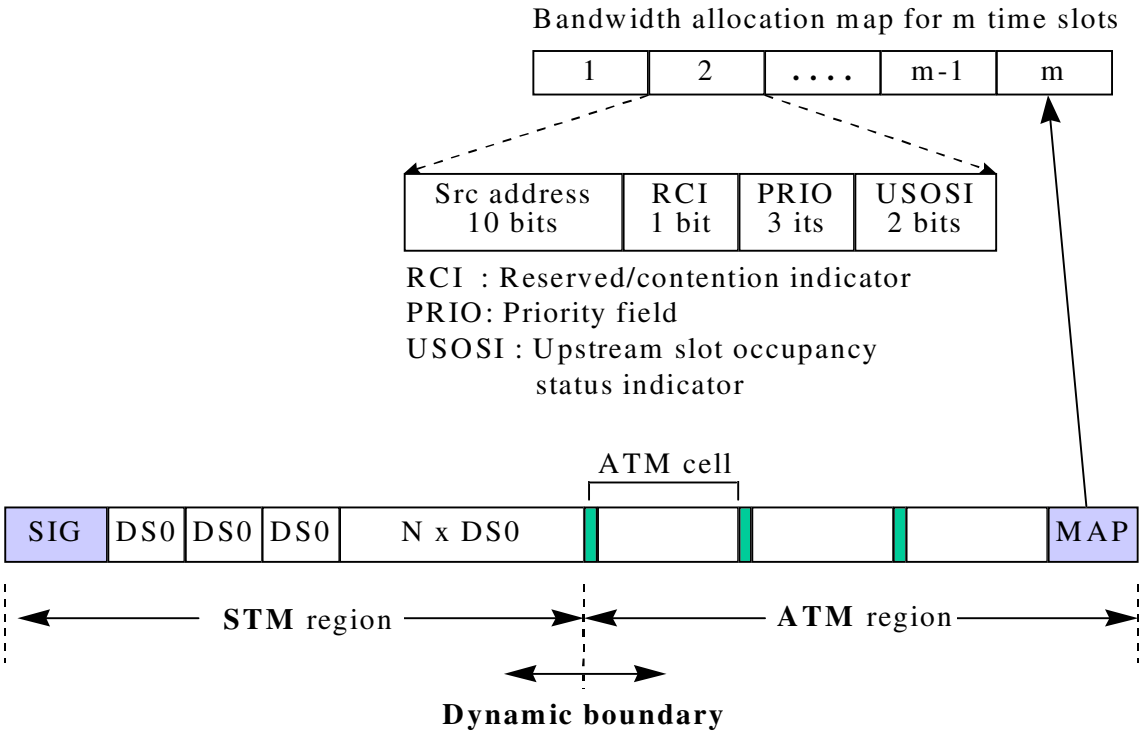
3.3.2 Adaptive Digital Access Protocol (ADAPt)

Described here is ADAPt protocol proposed by AT&T Bell laboratory. This protocol adapts to changing demands for a mix of STM(synchronous transfer mode) circuit and ATM(asynchronous transfer mode) cell mode applications, and efficiently allocates upstream and downstream bandwidth to a variety bursty and isochronous traffic sources. Figure 3-7 shows a view of an upstream frame structure. Accordingly, the frame is divided into STM and ATM regions. The boundary between the two regions can be changed dynamically. The STM region contains an STM signaling time slot, which is shared by contention access by all stations for STM call control and signaling. Stations transmit in a *"burst"* transmission mode in upstream. Each station uses guardband to avoid interference with adjacent time slots and uses preamble for clock and level recovery. The source address and bandwidth request field constitute the access control header in an ATM burst. If more than one station were to transmit in a contention time slot simultaneously, a collision will result; then the station

would apply a collision resolution scheme such as retransmission with random binary-exponential back-off.



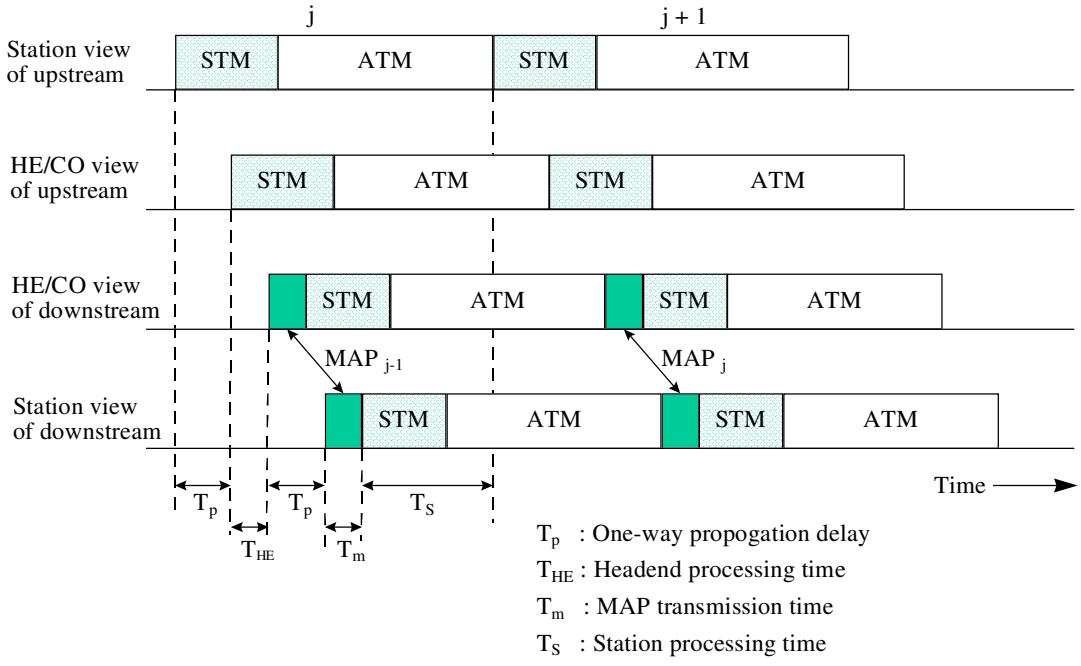
■ **Figure 3-7.** Upstream frame structure.



■ **Figure 3-8.** Downstream frame structure.

Figure 3-8 shows a view of a downstream frame structure. Accordingly, HE/CO transmits in a "continuous" transmission mode in downstream. Because the transmission channel is controlled and used only by the HE/CO, there is no need for guardbands and preambles. MAP region is used as the bandwidth allocation acknowledgments. Value m refers to the amount of ATM time slots in dedicated frame.

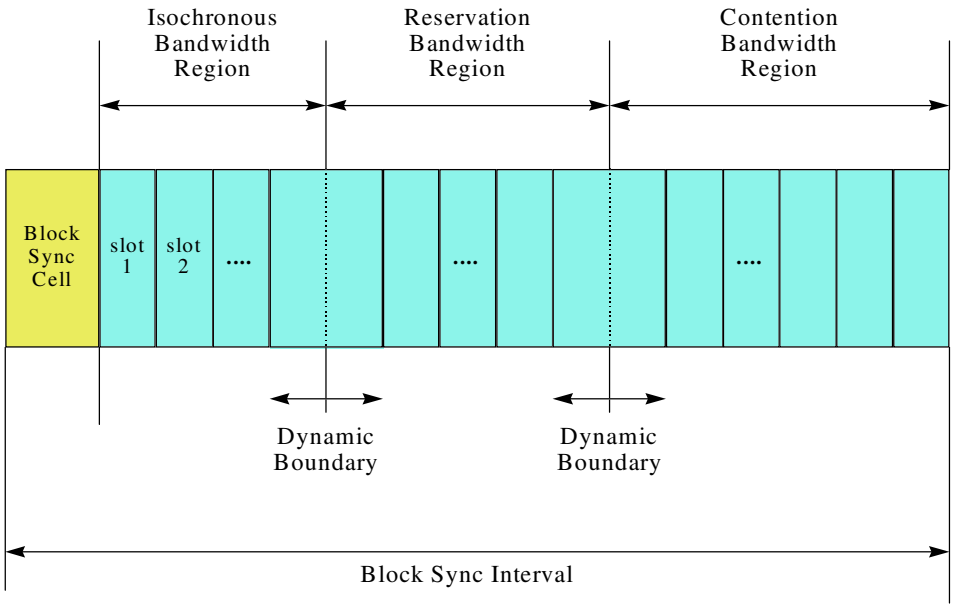
After undergoing an initial ranging process with the HE/CO, all stations have a common view with respect to time slot location and this timing synchronization is "fine-tuned" with the preamble of each slot. Figure 3-9 shows how stations' transmissions work. The MAP for the ATM contention time slots in frame j are received in frame j+1. The follow-up actions, if any, by the stations that transmitted an initial contention ATM cell in frame j will occur in frame j+2, so there is a pipelining effect on the ATM contention time slots over alternating frames.



■ **Figure 3-9.** Upstream/Downstream timing relationship.

3.3.3 UniLINK

The UniLINK protocol has been designed to operate within the community wide HFC infrastructure. It is based on the modified TDM (Time Division Multiplexing) concepts and supports a dynamic mixture of fixed (isochronous), demand-based reservation (dedicated) and random access (contention) regions in a block sync interval or cycle, as shown in Figure 3-10.



■ **Figure 3-10.** Dynamic allocation of bandwidth.

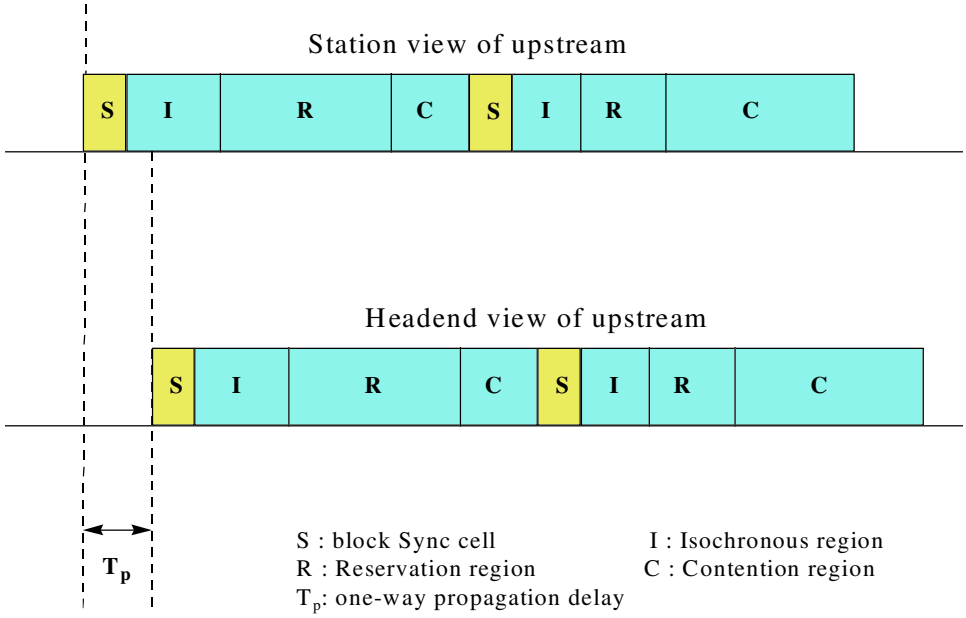
The isochronous assignment is the static allocation of slots to a particular station. This allows UniLINK to support applications that require fixed, guaranteed and jitter free bandwidth. The CBR service is suitable for this region. The reservation assignment is reservation-based and are granted as needed. These slots are contention free and provide high throughput with predictable delays. Note that the bandwidth assigned to a station is kept only for the interval assigned and relinquished on the subsequent block sync interval. Different from the isochronous assignment, this assignment may be applicable to the

applications with bursty traffic like VBR service. The contention region is available to all other traffic with a probability of collision and behaves similar to the slotted ALOHA protocol.

To line cells up precisely in their assigned slots, a station needs two critical pieces of information :

- a global timing reference signal
- knowledge of its own round trip delay to the headend

The slot time synchronization as well as slot assignments are controlled through a single station call *pacer* which may be the headend. The pacer transmits a Block Sync cell as a periodic timing reference signal at a fixed periodic rate. UniLINK uses a mechanism called *ranging* to obtain one's round trip delay. From the Block Sync timing information, a station knows precisely when it can transmit in a particular slot. Figure 3-11 shows the upstream block sync interval timing relationship between headend and stations.

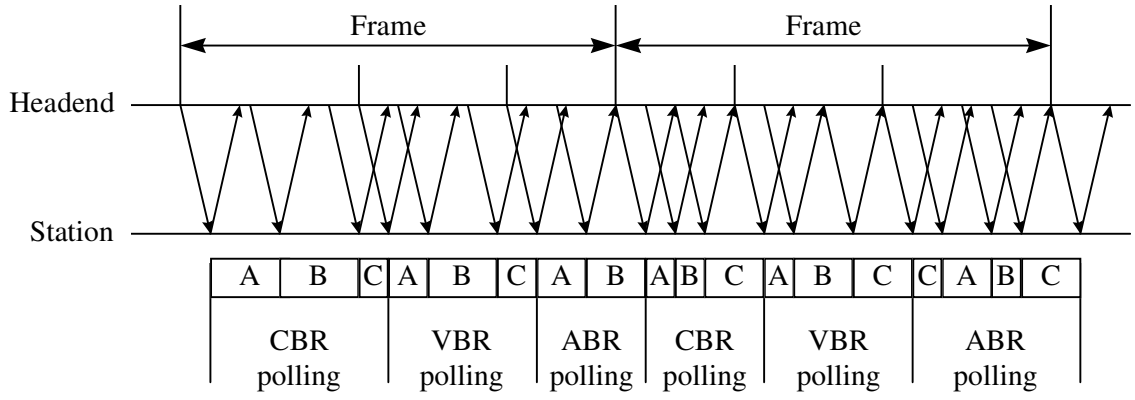


■ **Figure 3-11.** Timing relationship on upstream block sync interval.

Some observations should be made. First, this protocol allows a dynamic mixture of real-time and best-effort traffic. If most of the messages are best effort, which utilizes the contention region. The performance may be degraded to S-ALOHA. Second, because assigned reservation bandwidth is relinquished on the subsequent block sync interval, the new request for the reservation region is necessary. Since the requests for reservation and best-effort service are contention-based, performance may not be guaranteed.

3.3.4 Framed Pipeline Polling (FPP)

FPP protocol is presented by NEC corporation. This protocol is based on polling scheme and introduces pipeline processing of polling for efficient channel utilization in residential network. In addition, FPP supports dynamic bandwidth allocation according to various traffic types, from CBR (constant bit rate) and VBR (variable bit rate) to ABR (available bit rate). Skeleton of FPP is shown in Figure 3-12. Upstream and downstream have a fixed length frame structure. In each frame, polling is started from the first station and circulates all stations at least one time. In this scheme, all stations can send their data every frame and the delay variance is suppressed within one frame. This delay variance can be absorbed by a buffer and real-time transmission can be then achieved.



■ **Figure 3-12.** Polling scheme.

With this frame structure, polling circulates in the order of traffic types in each frame. As shown in Figure 3-12, in the first part of each frame, the controller polls all stations and allocates fixed amount of bandwidth for CBR traffic. After CBR pollings, the headend starts VBR pollings. It allocates bandwidth for all VBR traffic, where the amount of allocated bandwidth is controlled in order to guarantee the required average bandwidth. After allocating bandwidth for both CBR and VBR traffic, the remaining bandwidth in the frame is utilized for ABR traffic. The headend polls stations for ABR traffic. The number of polls for ABR depends on the remaining bandwidth. If the remaining bandwidth is large, polling circulates all terminals many times. If bandwidth is small, the headend polls several stations. For bandwidth allocation fairness, if the headend ends ABR polling at station n in a frame, it restarts ABR polling from the station n+1 in the next frame.

Stations synchronization is accomplished through initialization procedure while each station is ready to on-line. This procedure is executed through out of band signaling. The headend polls the new station for initialization. Upon receiving a poll, the non-initialized station sends an entry-request. Collision is resolved via a simple random retry algorithm. After receiving an entry-request, the headend measures round trip delay and calculates the adjustment time as discussed in section 3.3.1. Finally, the headend allocates a new address, adjust delay, and registers the station in a polling table.

3.4 Qualitative Comparison of MAC Protocols

We have surveyed a mount of MAC protocols above. They can be classified

into two categories : distributed protocols and centralized protocols. There is no central controller in distributed protocols like R-ALOHA protocols. The centralized protocols provide better timing mechanisms in avoiding collisions. This kind of protocols, proposed by many organizations, include MLAP, ADAPt, UniLINK and FPP. We also present our CATV MAC protocol, PCUP(Pipelined Cyclic Upstream Protocol), which will be detailed in the next chapter.

Both PCUP and MLAP support integrated services, and flexible contention and reservation modes of operation, where newly activated stations contend to establish themselves and then transmit on reserved time slots until they empty their queues. FPP works similarly to them besides that the station transmits its data immediately after the headend polls it. ADAPt and UniLINK all support a mixture of isochronous, reservation and contention bandwidth. The isochronous bandwidth is established by a setup process and exists before being released. The reservation bandwidth means that slots are on a per-request basis granted according to requests. And the contention bandwidth is randomly accessed. In order to characterize these protocols, we make a comparison summarized in Table 3-1. The entry of scheduling discipline means how connections‘ bandwidth requests are processed. These requests are either granted in a FCFS fashion or fairly allocated at the end of a cycle.

From table 3-1, we see that conventional MAC protocols can not meet the multi-media requirements. Although R-ALOHA can handle bursty traffic, it has the problem of unfairness and no QoS. In order to satisfy QoS requirements, centralized protocols with hybrid bandwidth allocation mechanism are more feasible.

	R-ALOHA	MLAP	ADAPt	UniLINK	FPP	PCUP
Distributed	✓					
Centralized		✓	✓	✓	✓	✓

Isochronous bandwidth			✓	✓		
Reserved bandwidth	✓	✓	✓	✓	✓	✓
Contention bandwidth	✓		✓	✓		
Scheduling discipline	N/A	fair scheduling	fair schedulin g	FCFS	FCFS	fair schedulin g
QoS		✓	✓	✓	✓	✓
timing implemented by	H/E	H/E STU	H/E STU	H/E STU	H/E	H/E
Headend complexity	..	....	....	....	....	....
Station complexity	.	..	.	..	..	.

■ **Table 3-1.** Features Comparison of proposed MAC protocols.

Among other centralized protocols, some observations should be made. In MLAP protocol, the headend uses the START-n algorithm to ensure that a station can transmit in a chain of contention-free transmissions for a long message. This collision resolution algorithm is well defined and proved to possesses better performance. In FPP protocol, the headend may poll every station about three times for CBR, VBR and ABR traffic types in a frame. This intensive polling increases the headend processing load. FPP and UniLINK protocols both transmit their CBR, VBR and ABR traffic in three different regions, such scheme achieves lower delay jitters over CBR traffic. In ADAPt and UniLINK protocols, contention based transmission will be the bottleneck while the traffic load is high.

4. Pipelined Cyclic Upstream Protocol

The HFC tree-and-branch topology with upstream and downstream channels presents a challenge in developing efficient protocols, especially for the many-to-one transmission in the upstream channels. The most important design issues are carrying multi-service traffic over a relatively long distance and overcoming the incapability of detecting upstream collisions by station themselves. Our solution, PCUP, is designed meet these criteria. The solution is described in the following parts: system overview, cycle membership control, station positioning, and transmission scheduling.

4.1 System Overall Description

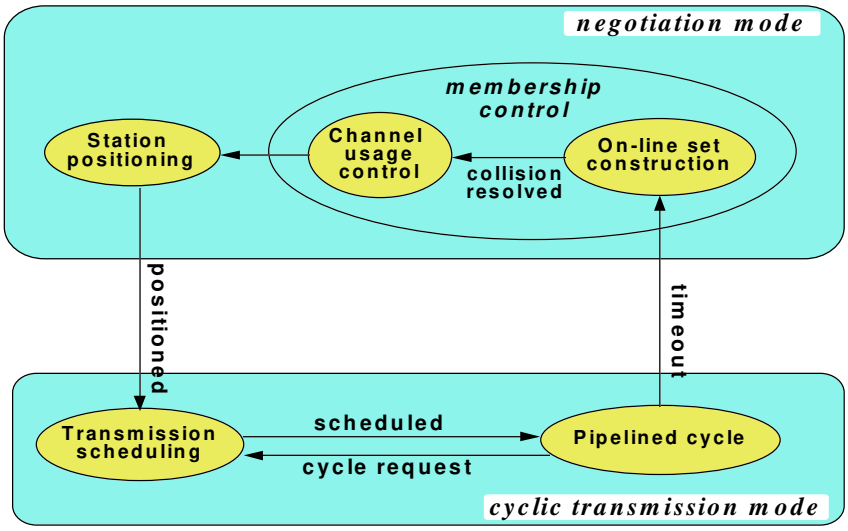
4.1.1 Overview

Stations, each with a propagation delay from the headend, are scattered randomly over the HFC network. We can neutralize stations' propagation offsets by synchronizing them. The synchronization process, sorting the on-line stations according to their propagation offsets from the headend, is called *station positioning*. A *membership control* is done periodically to update the set of on-line stations and the channel usage status. An efficient transmission scheduling algorithm is then applied, in each cycle, to schedule the transmission starting time and duration of each station so that cells appear to be pipelined, i.e. back-to-back, at the headend. These three mechanisms, namely, station positioning, membership control, and transmission scheduling, constitute PCUP.

We divide the PCUP operations into two transmission modes: cyclic transmission mode and negotiation mode as shown in Figure 4-1. In Figure 4-1, the condition to switch between the modes is triggered by a timer. PCUP runs a tree walk contention-based algorithm of the membership control in the

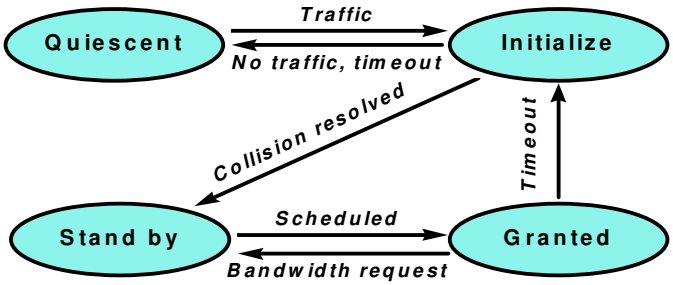
negotiation mode so that stations may join, to be on-line, or leave, to be off-line, the PCUP operations. This process is essential in keeping the system status updated.

After the tree walk algorithm, stations that are in the PCUP operations are arranged, by the station positioning algorithm, as a sequence sorted by their propagation offsets from the headend. Stations are aligned by the headend in order to schedule their precise transmission starting times. The alignment can neutralize station's propagation offset so that cells arrive at the headend as though they were sent with zero propagation delay.



■ **Figure 4-1.** State transition diagram of headend.

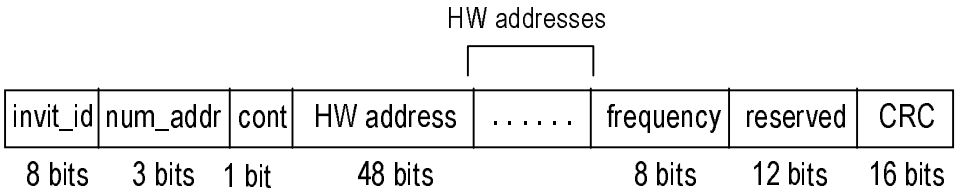
While in the cyclic transmission mode, the PCUP runs a contention-free slotted mechanism within the upstream. After scheduling the transmission starting times, the headend assigns transmission slots for each station by an allocation frame according to the station's buffer queue size reported in the previous cycle. A slot time is sufficient for transmitting an ATM cell. All stations, upon receiving the allocation frame, can transmit its data in its assigned slots within the cycle, as illustrated in Figure 4-2.



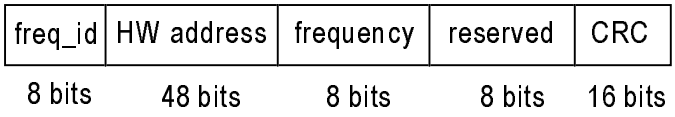
■ **Figure 4-2.** State transition diagram of station.

4.1.2 Data structures

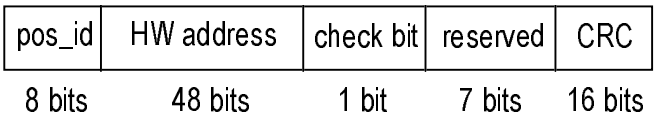
In PCUP, we will use four control frames, *HE.invitation, HE.balance, HE.position,* and *HE.schedule* for different operations. We present these frames in Figure 4-3 to Figure 4-6, and summarize some used variables in these frames into Table 4-1.



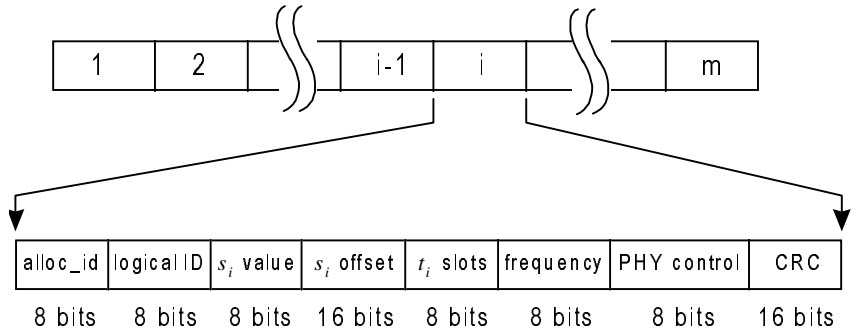
■ **Figure 4-3.** The frame structure of HE.invitation.



■ **Figure 4-4.** The frame structure of HE.balance.



■ **Figure 4-5.** The frame structure of HE.position.



■ **Figure 4-6.** The frame structure of HE.schedule.

We summarize some used variables and symbols into Table 4-1:

Entry name	Descriptions
invit_id/freq_id/ pos_id/alloc_id	All the *_id in control frames are used for the subscribers to perform the acknowledgment.
logical ID	This is a logical address of each station. The physical hardware address is mapped to a logical address.
HW address	Physical hardware address. It is used in *HE.invitation, HE.balance* and *HE.position*.
frequency	The channel usage control informs the station in which band to transmit its upstream data.

■ **Table 3-1.** Description of symbols.

A *Request_Table* is maintained in headend to monitor the whole system. The included fields of the *Request_Table* are shown in Table 4-2.

Attribute	Descriptions	Size (bits)
distance	The distance from the headend to the station.	12
start_time	The transmission starting time for the on-line station, which is broadcast by *HE.schedule* frame. The *start_time* includes two fields, *start slot* and *start offset*.	8+16
transmission_slots	The transmission duration time for the on-line station, which is broadcast by *HE.schedule*	8

	frame.	
logical ID	The field is used to maintain the mapping of logical address to physical address.	8+48
num_cells	This accumulates the consumed cells within a cycle by each on-line station.	24
assigned_channel	The field is used to record the assigned channel for the on-line station.	8

■ **Table 3-2.** Request_Table.

4.2 Membership control

In the negotiation mode, the headend has to do the following: 1) re-construct the set of on-line stations; 2) position the on-line stations into a sequence; 3) balance the usage of all upstream channels to alleviate the competition degree. Our membership control deals with the first and the third tasks.

4.2.1 On-line set construction

The set of on-line stations is established by membership control in the negotiation mode, which is triggered by a timer, *Group_Reset_Timer*. The timer is set periodically to 0.5 second or more. The headend issues a *HE.invitation* frame, as shown in Fig. 3-3, to the stations that do not belong to the set, i.e. not in *Request_Table*[1] and starts a tree walk algorithm to update the set of on-line stations. On-line stations which have not transmitted anything after the last membership control operation are considered off-line and will not receive the *HE.invitation frame*. The other on-line stations, which have transmitted

[1] As the of tree walk algorithm is time-consuming, invitation procedure only invites those that are not the current on-line stations.

something, will be still on-line with no need to send them the *HE.invitation* frame.

HE.invitation contains multiple hardware addresses. The field, *num_addr*, indicates the number of hardware addresses contained in the frame, while *cont* bit indicates whether this control frame extends to the next cell. The careful readers may find that the total length of these fields is 384 bits, which is equal to the size of an ATM payload.

4.2.2 Channel usage control

There may be about 500 subscribers contending for 17 upstream channels. It is believed that fixed allocation, say assigning 30 subscribers to each channel, is a poor solution. If an upstream channel has more stations on-line, the allocated slots per station will be fewer and the time spent in negotiate mode may be longer. Thus, dynamic channel assignment in upstream is necessary in order to balance the channel utilization.

We have a field, *assigned_channel,* in *Request_Table* which records the assigned channel for each on-line station. The number of cells transmitted in a channel can be calculated by summing up the *num_cells* of the entries having the same *assigned_channel* in *Request_Table*. The headend can rearrange the assignments of stations channels to balance the load according to the number of transmitted cells in the channel. The headend sends a control frame, *HE.balance*, to the re-arranged stations to notify them which channels to switch to.

Pseudo code for headend and station in Figure 4-7 summarizes the operations of cycle membership control which includes on-line set construction and channel usage control.

Pseudo code for headend

mark idle stations as off-line

run tree walk algorithm (for off-line stations to join)

collect statistics of channel usage

issue *HE.balance* to re-assign channels of stations if necessary

Pseudo code for station

IF *HE.invitation* received

run tree walk algorithm (if it is necessary to become on-line)

IF *HE.balance* received

tune the receiver and transmitter frequency

■ **Figure 4-7.** Pseudo code for cycle membership control.

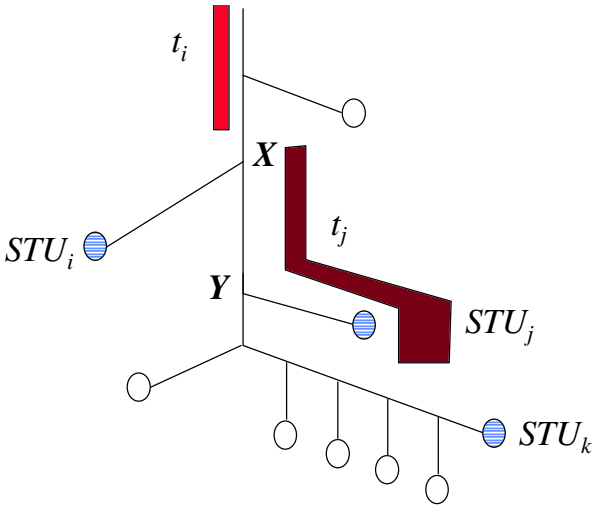
4.3 Station positioning

Our station positioning is the key to coordinate the stations' transmissions. It aims to neutralize station's propagation offset so that cells arrive at the headend as though they were sent with zero propagation delay. With the back-to-back transmission at the headend, the upstream channel will performs more efficiency without wasting. We explain the scheme by Figure 4-8. In Figure 4-8, X is the branching point of STU_i, and the difference of propagation delays between X to STU_i and X to STU_j is τ_{ij} ($\tau_{ij} = \tau_{jx} - \tau_{ix}$, where τ represents propagation delay). We can find out that the ideal situation at X can be modeled as

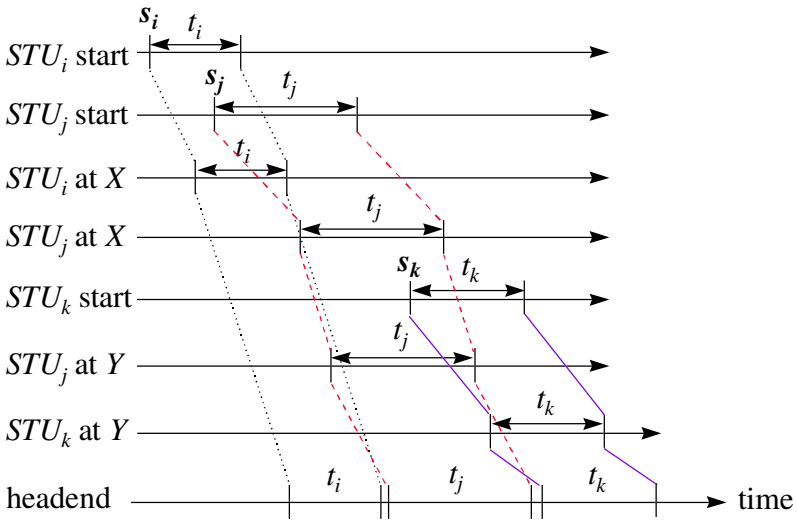
$$s_i + t_i + G = s_j + \tau_{ij}, \qquad (4\text{-}1)$$

where, s_i, $i = 1,2,.....N$, is the transmission starting time of STU_i, t_i is the allowed transmission duration for STU_i, G is the guard-band time between the

consecutive data cells from different STUs. Scenario of this ideal situation is described in a clearer way by the timeline in Figure 4-9. It is obvious that the headend needs to position the stations correctly in order to schedule transmissions in this way.



■ **Figure 4-8.** The tree-and-branch topology with data transmission where STU_i has transmitted, and the STU_j is transmitting. STU_j is the predecessor of STU_k and the successor of STU_i.



■ **Figure 4-9.** The example timeline of pipelined data transmission. The convergence point of STU_i and STU_j is X; the convergence point of STU_j and STU_k is Y. We find that the successor starts its transmission before the end of its predecessor's transmission.

The station positioning algorithm starts at headend. Headend sends a

HE.position frame (as shown in Figure 4-5) to each station that has been included by the tree walk algorithm as on-line. It starts a timer for each transmitted *HE.position*. Upon receiving *HE.position,* the station modifies a special field, *check bit,* and throws back the *HE.position* frame immediately, either by hardware or firmware. Headend computes the *distance,* from the headend to the station, as

$$\text{distance} = \lfloor (t_{rec} - t_{tx} - t_{overhead}) \div 2 \rfloor \times c \qquad (4\text{-}2)$$

where t_{rec} is the time headend receives the returned *HE.position,* t_{tx} is the time headend transmits *HE.position,* $t_{overhead}$ is the transmission delay and possible processing delay, and c is the signal propagation speed. A 16-bits timing counter with units of 61 *ns* is sufficient for the CATV length. Headend sorts these stations in the increasing order of the distance. The station positioning algorithm is summarized Figure 4-10.

FOR (all on-line STU_i)
    send *HE.position* and start a timer, *Timer[i]*
    WHILE (no ack of *HE.position*)
        increment *Timer[i]* by units of 61 *ns*
    Request_Table[i].distance = right-hand side of equation (4-2)
sort STUs by distance

■ **Figure 4-10.** Pseudo code of station positioning

4.4 Transmission scheduling

We are now ready to schedule the transmission starting time and duration of each station in this section. In order to help the headend to schedule the next cycle for the set of on-line stations, each station appends its buffer status, as requests shown in Table 4-3, at the end of its transmission duration.

Fields	Descriptions	Size

		(bytes)
b_i	number of best-effort cells at *STUi*	2
g_i/G_i	minimum/requested number of guaranteed cells at *STUi*	2/2
α_i/β_i	urgency of guaranteed/best-effort cells at STU_i	1/1

■ **Table 4-3.** Station slot requests.

Requests have two priority levels in PCUP: best-effort and guaranteed. Slots are allocated according to the reported requests. Even if empty buffer is reported, headend allocates one slot to the station so that it can report its status in the coming cycle. If the required transmission time for the summation of the reported buffer queue lengths exceeds the *Cycle_Time*, it would allocate a proper number of slots according to the traffic urgency parameters (α_i and β_i). The headend allocates transmission quota, t_i, for station i, as follows:

$$t_i = \begin{cases} (1)\ if\ \sum(b_i + W_i) < CBT \\ \quad max(b_i, 1) + W_i, \\ (2)\ if\ \sum(b_i + W_i) > CBT \\ \quad max(CBT \times \beta_i / \sum\beta_i, 1) + W_i, \\ (3)\ if\ \sum(G_i + b_i + W_i) < CBT \\ \quad max(G_i + b_i,\ 1) + W_i, \\ (4)\ if\ \sum(g_i + b_i + W_i) < CBT < \sum(G_i + b_i + W_i) \\ \quad max(g_i + b_i,\ 1) + W_i + ((CBT - \Sigma(g_i + b_i)) \times (G_i - g_i) / \Sigma(G_i - g_i)), \\ (5)\ if\ (CBT - \sum b_i) < \sum(g_i + W_i) < CBT \\ \quad max((CBT - \sum(W_i + g_i)) \times \beta_i / \sum\beta_i,\ 1) + W_i + g_i, \\ (6)\ if\ \sum(g_i + W_i) > CBT \\ \quad max((CBT - \sum W_i) \times \alpha_i / \sum\alpha_i,\ 1) + W_i, \end{cases}$$

(4-3)

where *CBT* is the *Cycle_Time* and W_i is the guard-band time overhead. The

situations for these six cases are:

- ***Case (1)***

  There is only best-effort traffic. Summation of all best-effort requests does not exceed the link capacity; thus, all of them can be served.

- ***Case (2)***

  There is only best-effort traffic. Summation of all best-effort requests exceeds the link capacity; thus, these best-effort cells are served partially and proportionally according to their urgency parameters, β_i.

- ***Case (3)***

  Summation of all best-effort and guaranteed services does not exceed the link capacity; thus, all of them can be served.

- ***Case (4)***

  Summation of all best-effort cells and minimum guaranteed cells can be served. The left-over capacity is used to serve as many, up to G_i-g_i for station i, guaranteed cells as possible.

- ***Case (5)***

  Summation of all minimum guaranteed services is less than the link capacity, but the remaining capacity is not enough for all the best-effort cells. Thus, these best-efforts cells are served partially according to their urgency parameters, β_i. β_i is used as the weight of station i in distributing the left-over capacity.

- ***Case (6)***

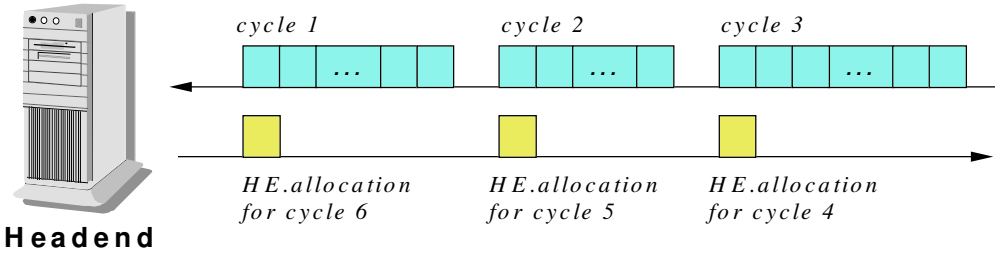
  The case is the worst situation where the link capacity is less than the

summation of minimum guaranteed services. Thus, the guaranteed cells are served partially by their urgency parameters, α_i. α_i, again, is used as the weight to distribute the capacity.

After that, the headend then computes the transmission starting time, s_i, precisely as follows:

$$s_i = \sum_{j=1}^{i-1} t_j - \tau_i \qquad (4\text{-}4)$$

Then, headend can assign a proper starting time and transmission duration time by the allocation frame, *HE.schedule*. The structure of *HE.schedule* is given in Figure 4-6.



■ **Figure 4-11.** Look-ahead allocation.

Note that with the possible long propagation delay, the headend may need to pre-allocate the *HE.schedule* frame several cycles ahead, as illustrated in Figure 4-11. The amount of this look-ahead has to be larger than the longest propagation delay. Since the propagation delay is usually small compared to the cycle time, 323 μs vs. 50 ms in some of our simulations, we need to look ahead only one cycle in most cases.

4.5 Summary of PCUP

We now summarize the PCUP operations in Figure 4-12 and Figure 4-13. The pseudo code includes: station operations and headend operations.

CASE (*HE.schedule* received)
transmit cells in allocated time slots
request the buffer status of its own at the end of

transmission

CASE (*HE.invitation* received)

run tree walk algorithm (if it is necessary to become on-line)

CASE (*HE.balance* received)

tune the receiver and transmitter frequency

CASE (*HE.position* received)

throw back the frame immediately

■ **Figure 4-12.** Pseudo code of station operations.

IF (time up of *Group_Reset_Timer*)

cycle membership control (in Figure 4-7).

station positioning (in Figure 4-10).

ELSE

seize a cell from input buffer

process the cell, upgrade *Request_Table,* ack to station

issue *HE.schedule* frame (in Figure 4-6) if all the on-line stations requesting are collected

■ **Figure 4-13.** Pseudo code of headend operations.

5. Simulation study

We show the numerical results in this chapter regarding loss ratio, throughput, access delay, cell delay variance and fairness. We first examine the HFC network configuration and traffic models in section 5.1 and section 5.2., followed by the simulation results of R-ALOHA, UniLINK and PCUP .

5.1 Network configuration

We assume the values of some configuration parameters based on the existing proposals [??]:

- A 40 MHz band can be divided into multiple upstream channels. Each of them can be 1 MHz to 6 MHz wide and 1.6 Mbps to 10 Mbps in capacity. According to [?], we assume the upstream frequency range to be 8-26.5 MHz and 1.544, 2.048, 6 and 10 Mbps transmission rate per channel. By this assumption, 17, 14, 5 and 3 upstream channels can be used simultaneously.
- Length of an upstream cell is assumed to be 424 bits (53 bytes), which is equal to 275 μs transmission time with the 1.544 Mbps transmission rate. Moreover, stations have a limited buffer size of 500 cells. Each station's hardware addresses is 48 bits.
- The fiber node extends the services from the headend to the customer's neighborhood, covering about 500 to 2000 homes by several branches. Each branch serves 125 to 500 homes. That means an upstream channel is shared by about 30, 35, 100 and 167 subscribers respectively. The scale of network is assumed to be 80 km.

5.2 Traffic models

Three types of traffic models are applied in the simulations:

- ***Traffic model A : All best-effort ABR***

  The first traffic model contains only LAN like traffic, e-mail, file transfer, and etc., to demonstrate the protocol capability to support the existing data services. Poisson is assumed to be the source model.

- ***Traffic model B : ABR and CBR***

  The CBR applications contribute 50% traffic load, the rest 50% remains to be ABR. The PCR(Peak Cell Rate) [16] generated by a common CBR telephony application is 64 Kbps. This model can test the stability of the MAC protocols.

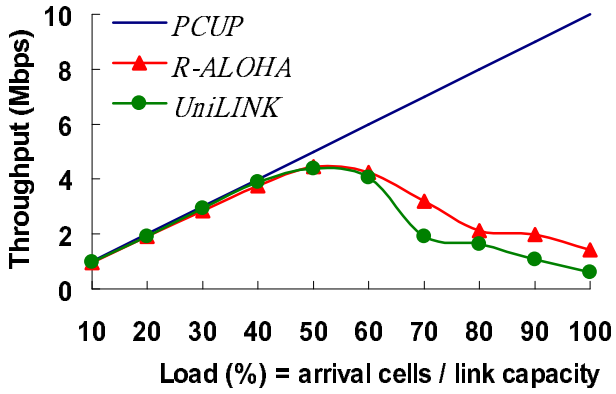
- ***Traffic model C : ABR, CBR, and VBR***

  The VBR applications present 30% traffic, CBRs pump 30%, and the rest is for ABR services. The ON/OFF process is used to model VBR services. The lengths of ON and OFF periods are exponentially distributed. In this model, we can measure the quality of service of the ABR applications under the heavy traffic presented by the VBR and CBR applications.

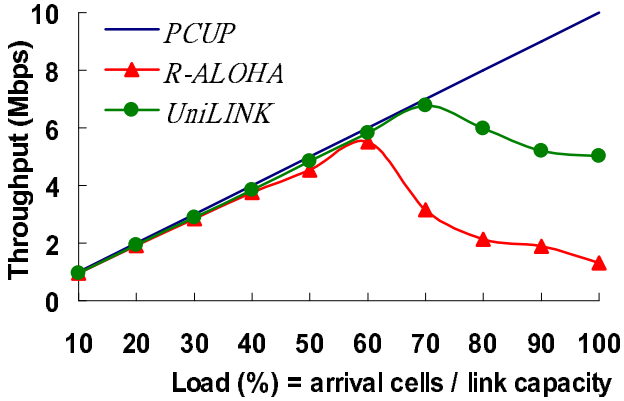
5.3 Numerical results

5.3.1 System throughput

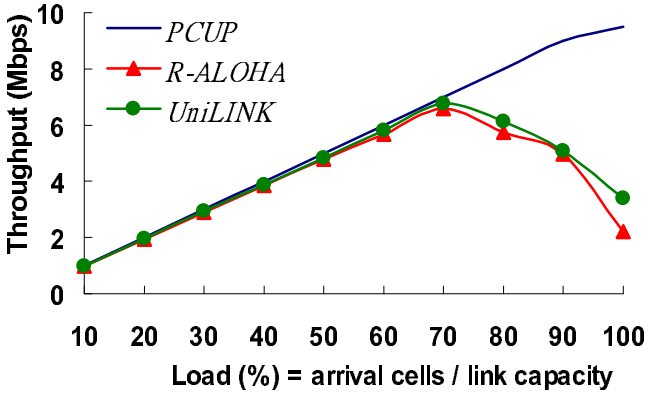
In Fig. 5-1, Fig. 5-2 and Fig. 5-3, we can find that the throughput of R-ALOHA and UniLINK are not ideal under heavy traffic. This scenario is due to their contention bandwidth. In traffic model A, UniLINK behaves similarly to S-ALOHA. Since a UniLINK with ABR traffic has to contend the slots each time, it performs even worse than R-ALOHA. Because of PCUP's perfect centralized bandwidth scheduling, it achieves excellent channel throughput under various traffic types. We also see that the curves for PCUP are close to the theoretical bounds and exhibit little difference for traffic models A, B and C. The maximum throughput equals to 98.38%. The 1.62% left-over is due to the $2\mu s$ guard-band time we put and a fraction of slot time that is not enough for a complete slot within the whole cycle.



■ **Figure 5-1.** Throughput of PCUP, R-ALOHA and UniLINK under traffic model A. The channel capacity is 10 Mbps.

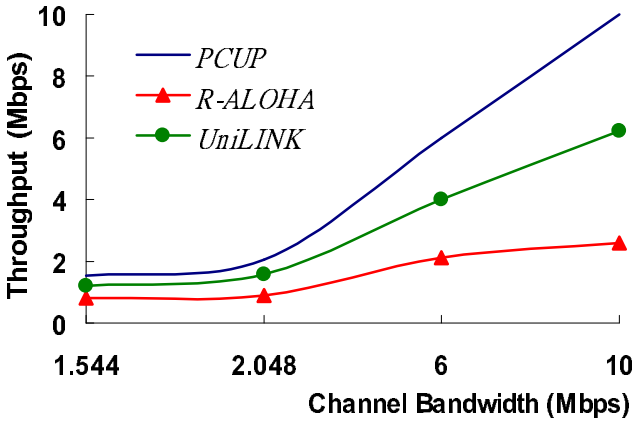


■ **Figure 5-2.** Throughput of PCUP, R-ALOHA and UniLINK under traffic model B. The channel capacity is 10 Mbps.



■ **Figure 5-3.** Throughput of PCUP, R-ALOHA and UniLINK under traffic model C. The channel capacity is 10 Mbps.

In Fig. 5-4, PCUP obtains higher throughput than the R-ALOHA and UniLINK no matter what the channel capacity is. At 1.544 Mbps channel bandwidth and 90% traffic load, PCUP has throughput 15% higher than UniLINK's, while at 10 Mbps channel bandwidth and the same traffic load, PCUP has throughput 37.6% higher than UniLINK's. UniLINK performs worse than PCUP due to the effect of contention bandwidth. But it works better than R-ALOHA since it provides isochronous bandwidth assignment and reservation scheme to support CBR and VBR traffic respectively.

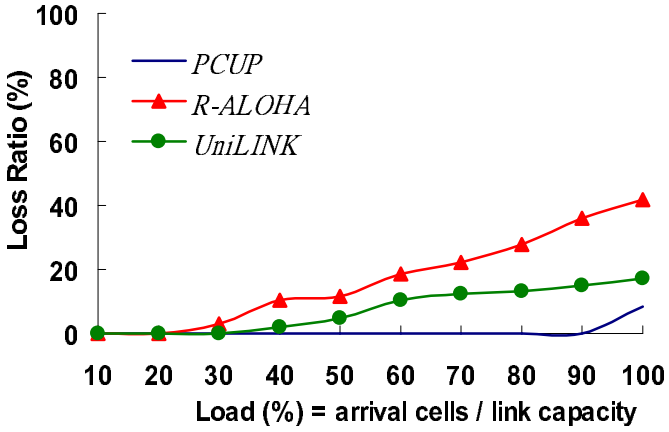


■ **Figure 5-4.** Throughput of PCUP, R-ALOHA and UniLINK under different channel capacities. The traffic model is C and traffic load is 90%.

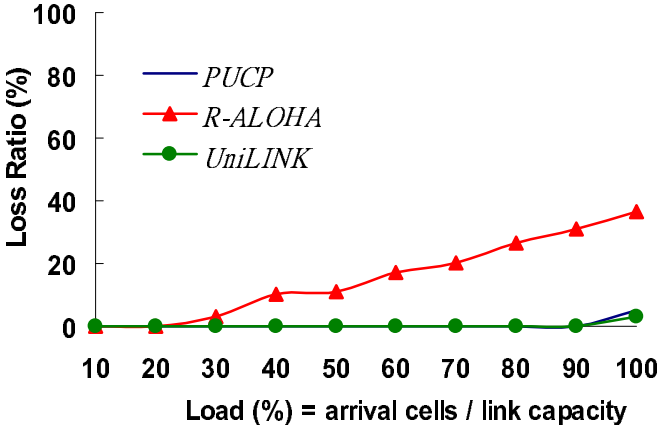
5.3.2 Loss ratio

After examining the numerical result of throughput, we investigate the channel performance in another aspect. Now we focus on the loss ratio, which is defined to be lost cells over arrival cells. From Fig. 5-5, it is obvious that PCUP does well than R-ALOHA and UniLINK over ABR traffic since R-ALOHA and UniLINK are contention-based in processing ABR traffic requests. In Fig. 5-6, we find that UniLINK has better performance than PCUP. UniLINK has only 3.1% loss ratio when the system is fully loaded, while PCUP has 5.1% loss ratio. This result is expected since UniLINK provides isochronous bandwidth over CBR traffic, while PCUP satisfies minimum CBR and VBR requests first. PCUP is still

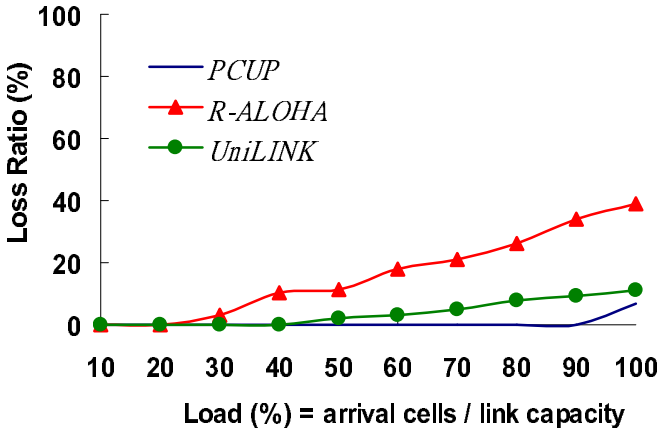
remarkable in dealing with CBR traffic. Comparing Fig. 5-7 with Fig. 5-5, the curves are similar, but UniLINK achieves lower loss ratio of VBR traffic. This scenario is due to applying reservation scheme over VBR traffic. In R-ALOHA protocol, every cell is treated in the same way, i.e. no priority. So it behaves in a similar way under various traffic types.



■ **Figure 5-5.** ABR traffic lost ratio of PCUP, R-ALOHA and UniLINK under traffic model C.



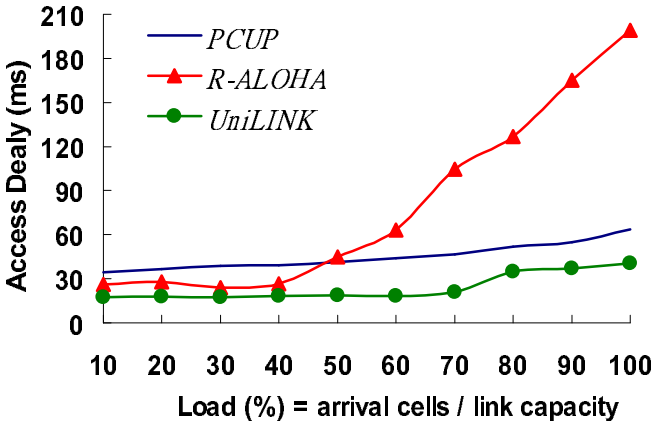
■ **Figure 5-6.** CBR traffic lost ratio of PCUP, R-ALOHA and UniLINK under traffic model C.



■ **Figure 5-7.** VBR traffic lost ratio of PCUP, R-ALOHA and UniLINK under traffic model C.

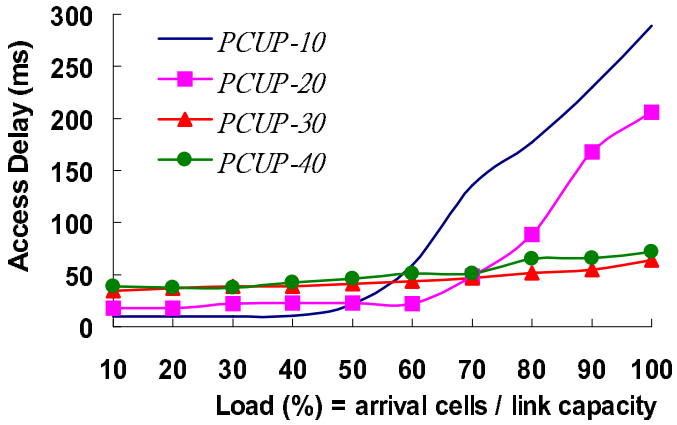
5.3.3 Access delay

In Fig. 5-8, R-ALOHA has larger access delay when traffic load is high. Because of higher collision ratio under heavy traffic, collided cells may be retransmitted many times. Thus access delay grows up accordingly. UniLINK performs well on access delay since CBR and ABR cells, which are generated in a frame interval, can access time slots in the same frame. CBR traffic uses the specified isochronous bandwidth and ABR traffic contends for contention bandwidth. In order to fully utilize channel bandwidth, PCUP gathers all bandwidth requests and schedules them together. So cells, which are generated in a frame interval, may not be transmitted in the same frame. Due to perfect bandwidth scheduling, PCUP still achieves low access delay under heavy traffic.



■ **Figure 5-8.** Access delay of PCUP, R-ALOHA and UniLINK under traffic model A.

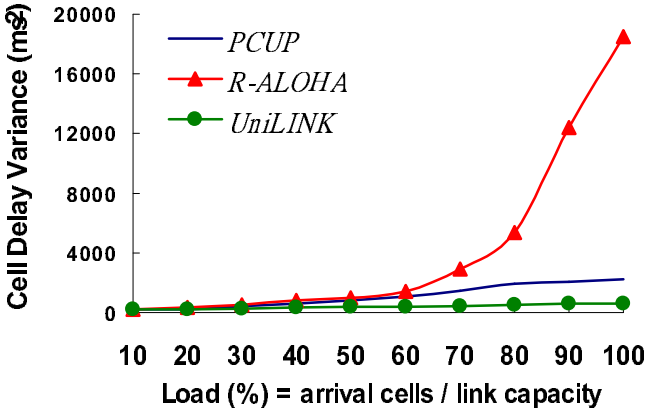
Now we focus on the impact due to the cycle time. In Fig. 5-9, something interesting can be observed. The access delay increases dramatically under heavy traffic when the cycle time is small. We can explain this scenario by an example. Consider the subway systems, there are two alternatives : heavy-system and light-system. In the heavy-system, high capacity trains are operated with lager train inter-arrival time. In the light-system, low capacity trains are operated with smaller train inter-arrival time. The parameters of these two systems are adjusted so that their transportation capacities per hour are the same. When the load is high, the heavy-system performs better because the probability that all existing passengers can be on board is higher than that of the light-system where more passengers may have to wait for the next train. When the load is low, the light-system is better because its shorter train interarrival time.



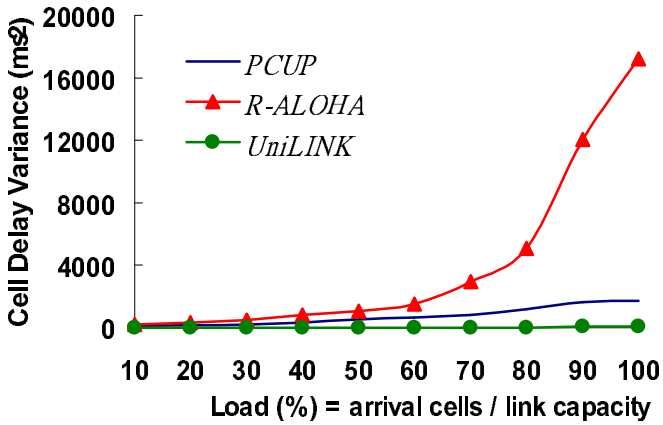
■ **Figure 5-9.** Access delay of PCUP under different cycle times. The traffic model is C and the channel bandwidth is 10 Mbps. PCUP-10, for example, means the cycle time is 10 ms.

5.3.4 Cell delay variance (CDV)

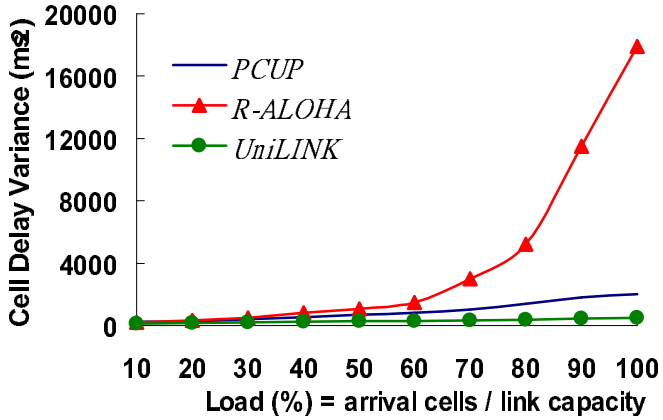
The CDV is the guideline for examining the jitter performance of the MAC protocol in processing real time traffic. From Fig. 5-10, Fig. 5-11 and Fig. 5-12, R-ALOHA can not achieve the QoS requirement. This result is due to its random access control and single-priority treatment to all traffic types. Because of providing isochronous bandwidth, UniLINK gets excellent CDV performance of CBR traffic. It also performs well over ABR and VBR traffic since they are transmitted on the specified regions. PCUP is still remarkable in CDV performance under high throughput.



■ **Figure 5-10.** ABR traffic cell delay variance(CDV) of PCUP, R-ALOHA and UniLINK under traffic model C. The channel bandwidth is 10 Mbps.



■ **Figure 5-11.** CBR traffic cell delay variance(CDV) of PCUP, R-ALOHA and UniLINK under traffic model C. The channel bandwidth is 10 Mbps.

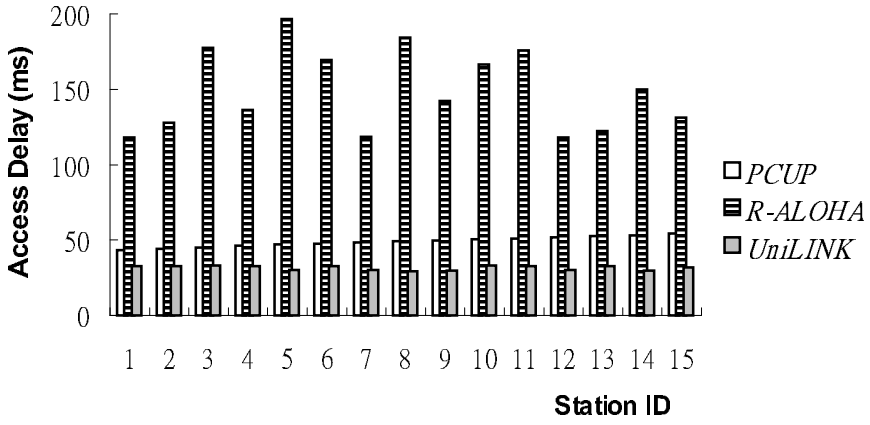


■ **Figure 5-12.** VBR traffic cell delay variance(CDV) of PCUP, R-ALOHA and UniLINK under traffic model C. The channel bandwidth is 10 Mbps.

5.3.5 Fairness

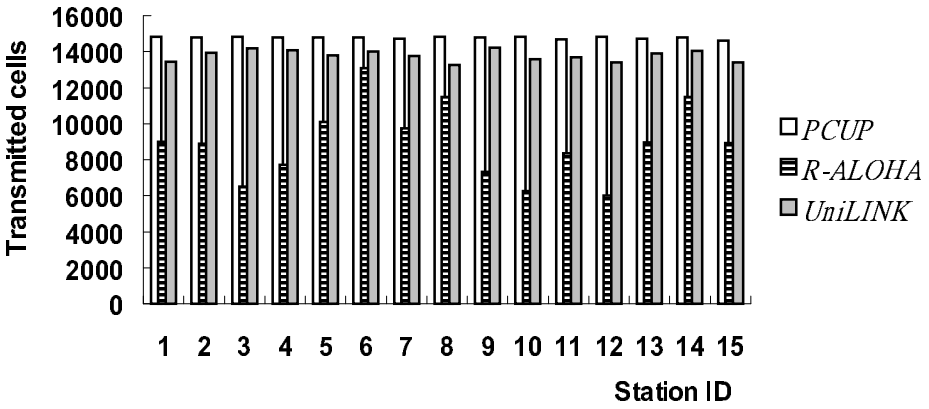
Fairness is another issue while considering performance of an interactive CATV MAC protocol. In Fig. 5-13 and Fig. 5-14, we randomly select 15 stations from 167 stations sharing the 10 Mbps channel to compare their access delay

and throughput. These 15 stations are sorted by their propagation delays with station 1 being the nearest to the headend. It is obvious that R-ALOHA is unfair. The reason is that a station can monopolize a slot in every consecutive frame once it successfully captures a slot. Thus, other stations may starve and have higher access delay, when most slots are reserved. In contrast, if a time slot is successfully reserved for some station, the station receives a lower access delay. For example, station 12 has an average access delay of 80.8 ms, but station 8 has 229.8 ms. PCUP and UniLINK are fair and latency guaranteed. Since the bandwidth scheduling of PCUP takes the stations' offset into consideration, it results in larger access delay for farther stations and lower access delay for nearer stations.



■ **Figure 5-13.** Access delay of PCUP, R-ALOHA and UniLINK under traffic model C. The channel bandwidth is 10 Mbps and traffic load is 90%.

From the view point of successfully transmitted cells per station, we see that, in Fig. 5-14, PCUP performs very well. Because of the FCFS scheduling of bandwidth requests, UniLINK behaves a little unfair. R-ALOHA still results in starvation at some stations.



■ **Figure 5-14.** Successfully transmitted cells of PCUP, R-ALOHA and UniLINK under traffic model C. The channel bandwidth is 10 Mbps and traffic load is 90%.

6. Performance Evaluation

6.1 System Definition

After examining the simulation outcomes of PCUP, it is worthy to verify the numerical result through mathematical language. Consider a PCUP system whose cycle length is T and the number of stations per channel is N. Note that, in order to prevent channels from cross-talking, number of upstream channels is highly dependent on channel capacity. Therefore N is dependent on channel capacity for load balance consideration. For a Poisson traffic source, the probability that n new packets arrive in a cycle is

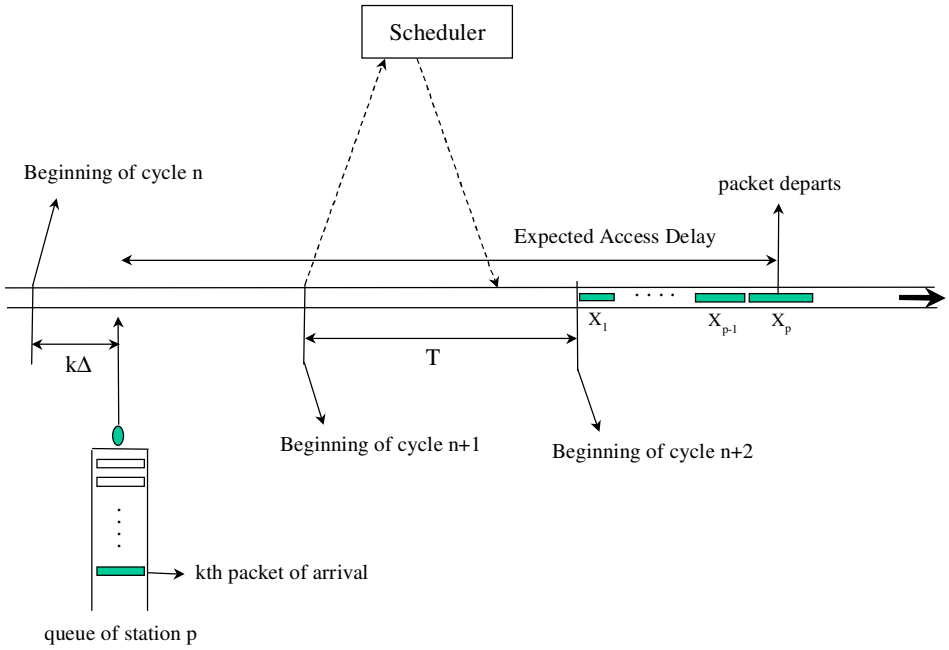
$$\Pr\{\text{ n new arrivals }\} = \frac{e^{-\lambda T}(\lambda T)^n}{n!} \quad \text{..... (6-1)}$$

where $\lambda=\Lambda/N$ is the arrival rate per second of each station and Λ is the system arrival rate. Define μ to be the system service rate. Thus $\Lambda<\mu$ is the essential assumption for a stable system. For this reason, we assume that in one time-slot interval, there is at most one packet arriving in the station queue. If the time-slot interval is τ, we have $\mathbf{M} \equiv \mathbf{T}/\tau$ as the number of time-slots in one cycle. In this assumption, it can be shown that the expected arrival instant of the kth packet is $k\Delta$ where $\Delta=T/(n+1)$ and $k \le n \le \mathbf{M}$.

6.2 Access Delay Analysis

As illustrated in Figure 6-1, the access delay of the kth packet arrival of station p during cycle n is easily decomposed into four parts. The first part equals to residual cycle time. The second part equals to one unavoidable cycle time due to bandwidth request for cycle n+2. The cycle time **T** is assumed to be longer than that of two-way propagation delay plus scheduler processing time.

The third part it encounters due to aggregated service time of stations whose position is closer to headend. And the last part it experiences due to the service time of the packets that arrive prior to him in cycle n.



■ **Figure 6-1.** Timing relationship.

Thus the access delay of the kth arrival packet of station p can be formulated as:

$$Y_{kp} = T - k\Delta + T + \tilde{X}_1 + \tilde{X}_2 + \cdots + \tilde{X}_{p-1} + (k-1)\tau \quad \text{..... (6-2)}$$

where $\tilde{X}_i$ is the service time distribution of the station i in a cycle, and 1≤ i ≤ p-1, 1≤ p ≤ **N**. Since the service time of these stations are independently and identically distributed, we have $E[\tilde{X}_1] = E[\tilde{X}_2] = \cdots = E[\tilde{X}_{p-1}] \equiv E[\tilde{X}]$ and :

$$E[\tilde{X}] = \sum_{\alpha=1}^{M} \alpha \cdot \tau \cdot \Pr\{\alpha \text{ arrivals in a cycle}\} = \sum_{\alpha=1}^{M} \alpha \cdot \tau \cdot \frac{e^{-\lambda T}(\lambda T)^{\alpha}}{\alpha!}$$
$$= \tau \sum_{\alpha=1}^{M} \frac{e^{-\lambda T}(\lambda T)^{\alpha}}{(\alpha-1)!} \quad \text{.....(6-3)}$$

With equation 6-3, we may transfer the 6-2 into expectation form as follows:

$$E[Y_{kp} \mid \tilde{v} = n, kth\ packet] = E[2T - k\Delta + (k-1)\tau + \tilde{X}_1 + \tilde{X}_2 + \cdots + \tilde{X}_{p-1}]$$
$$= 2T + (p-1)\tau \sum_{\alpha=1}^{M} \frac{e^{-\lambda T}(\lambda T)^{\alpha}}{(\alpha-1)!} + (k-1)\tau - \frac{k}{n+1}T$$

We may therefore remove the condition on k as follow:

$$E[Y_p \mid \tilde{v} = n] = \sum_{k=1}^{M} E[Y_{kp} \mid \tilde{v} = n, kth\ packet] \Pr\{kth\ packet\}$$
$$= \sum_{k=1}^{M} E[Y_{kp} \mid \tilde{v} = n, kth\ packet] \cdot \frac{1}{n}$$
$$= 2T + (p-1)\tau \sum_{\alpha=1}^{M} \frac{e^{-\lambda T}(\lambda T)^{\alpha}}{(\alpha-1)!} + \frac{1}{n}\sum_{k=1}^{n}\left[(k-1)\tau + \frac{kT}{n+1}\right]$$
$$= \frac{3T}{2} + (p-1)\tau \sum_{\alpha=1}^{M} \frac{e^{-\lambda T}(\lambda T)^{\alpha}}{(\alpha-1)!} + \frac{(n-1)\tau}{2}$$

Consequently, the average access delay of station p is

$$E[Y_p] = \sum_{n=1}^{M} E[Y_p \mid \tilde{v} = n] \Pr\{\tilde{v} = n\}$$
$$= \sum_{n=1}^{M}\left(\frac{3T}{2} + (p-1)\tau \sum_{\alpha=1}^{M} \frac{e^{-\lambda T}(\lambda T)^{\alpha}}{(1-1)!} + \frac{(n-1)T}{2}\right)\frac{e^{-\lambda T}(\lambda T)^{n}}{n!} \quad \text{..... (6-4)}$$

and therefore the average access delay is

$$E[Y] = \sum_{p=1}^{N} E[Y_p] \Pr\{pth\ station\} = \frac{1}{N}\sum_{p=1}^{N} E[Y_p] \quad \text{..... (6-5)}$$

6.3 Illustrative Results

Figure 6-2 shows the access delay of station p. Smaller value p implies that it is closer to headend than that with larger p. Obviously, according to transmission starting equation 4-1, the transmission starting time of station who is closer to the headend will

6.4 Discussions

7. Common Agreement of IEEE 802.14 Working Group Committee

7.1 Physical Layer Specification

The 802.14 physical layer standard specification supports asymmetrical bi-directional transmission of signals in the HFC network. The HFC network is a point-to-multipoint, tree and branch access network in the downstream direction, and a multipoint-to-point, bus access network in the upstream direction.

The frequency from 100MHz to the upper frequency limit supported by the cable plant is allocated for downstream transmission. Within this frequency band, FDM channelized method is utilized to transmit data from headend to stations. The sub-split band that ranges from 5 to 42 MHz is allocated for upstream transmission. Additional frequency bands for upstream transmission are intended for future use, called “mid-split” and “high-split” bands. The mid-split extends from 5 to 108 MHz. The high-split covers the range between 5 to 174 MHz.

64QAM and 256QAM modulation schemes are applied for downstream transmission. QPSK and 16QAM are adapted in upstream direction. The propagation delay is normally 5 usec/km for fiber, and 4 usec/km for the coaxial cable.

7.2 Medium Access Control Specification

7.2.1 Station Addressing

This standard provides two addressing mechanisms to distinguish one

station from another. One is traditional IEEE 802 MAC addressing, which utilizes 48 bits to identify one station, and the other refers to local identifier(LI) that is meaningful only within a single 802.14 network.

The MAC address is not normally used in the 802.14 MAC protocol. Instead, one or more 14 bits LIs are assigned to the station by headend. The first LI assigned to a station is called the primary LI. The primary LI is used for MAC, PHY control, security and data transfer. LIs are also used to identify broadcast and multicast groups. When a multicast group is formed, either by a station or the headend, the headend allocates a LI to the multicast group and associates it internally with the 48 bits multicast MAC address. As stations are added, by 48 bit MAC address, to the multicast group, the headend must send the new station a message to add the LI of the multicast group to its list of recognized LIs. If the multicast group is encrypted then the headend must also inform the new station of the keys that are pertinent to the multicast group. These messages are sent in unicast cells directed to the primary LI of the new station. Note that, well known LI 0x3FFE is used during station registration.

7.2.2 Channel Hierarchy

The downstream channel is composed of 6 octet allocation units. A single unit can be assigned the idle pattern or multiple units can be used to create ATM cells or variable length fragments. The upstream channel is multiple access medium. Each channel is divided into a series of 8 octets length *minislots*. Each minislot is implicitly assigned a 16 bits identifier by the headend. The number will wrap to zero at a network dependent value. Multiple minislots can be concatenated to ATM cells or variable length fragments. Following is the brief introduction of upstream and downstream channel hierarchy.

7.2.2.1 Upstream Channel Hierarchy

Table 7-1 illustrates all upstream MAC messages under the operation of 802.14 network. PDU refers to Payload Data Unit.

Message Type	Message Name	Size (octet)	Functionality
PDU formats	PDU type octet	1	Indicate type of PDU
	ATM cell PDU	53	Carry ATM cell
	Variable length fragment PDU	variable	Carry LLC traffic
MAC layer management	Invitation Response miniPDU	8	Response to headend invitation
	Request miniPDU	8	Request ATM cells or variable length fragments
	CBR allocation request	7	Request continuously available channel capacity for CBR traffic
	Multicast address add	17	Request headend add a 48 bits MAC address to a 48 bits multicast address
	Multicast address delete	17	Instruct headend to remove a station from a group address mapping

■ **Table 7-1**. Upstream channel hierarchy.

Note that, CBR allocation request, multicast address add and delete messages are carried through ATM cells. Multiple upstream management messages may be packet into a single ATM cell but are not allowed to cross cell boundaries. The ATM cells with PT=0B010 are preassigned as MAC layer management messages. As invitation response miniPDU and request miniPDU are transferred by a minislot, CRC field that deals with error control is essential.

7.2.2.2 Downstream Channel Hierarchy

Table 7-2 illustrates all upstream MAC messages under the operation of 802.14 network.

Message Type	Message Name	Size (octet)	Functionality
PDU formats	PDU type octet	1	Indicate type of PDU
	ATM cell PDU	53	Carry ATM cell
	Variable length fragment PDU	Variable	Carry LLC traffic
	Idle segment	Variable	Indicate idle headend
Bandwidth management	ATM cell grant	8	Inform granted ATM cells
	Variable length fragment grant	8	Inform granted variable length fragments

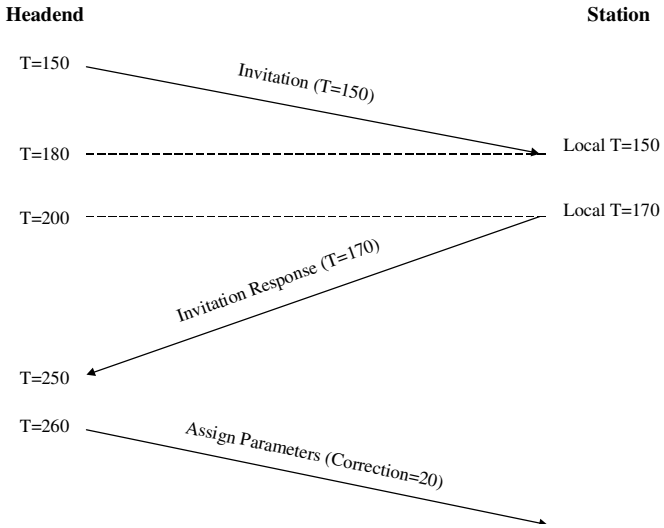
	Request minislot allocation	variable	Specify the location of minislots available for contention as well as collision resolution parameters
	Request minislot contention feedback	6	Inform stations of contention status of each request minislot
	Extended bandwidth request feedback	6	Acknowledge the extended bandwidth request
	CBR allocation feedback	7	Acknowledge the CBR allocation request
	Request PDU feedback	6	Acknowledge the PDU bandwidth request
MAC layer management	Invitation cell	Variable	Invite unregistered stations
	Signature cell	18	Provide timing reference for all stations
	Assign parameter	Variable	Introduce a new station to the network
	PHY power adjust	4	Adjust the power level of station
	PHY range adjust	6	?
	PHY upstream channel set	Variable	
	PHY downstream channel set	Variable	
	Request station statistics	2	Request current statistic information of the station
	Request station parameters	2	Request current PHY and MAC parameters of the station
	MAC LI add	4	Add another LI to the local LIs recognized by this station
	MAC LI delete	4	Delete the LI from the set of local LIs recognized by this station

■ **Table 7-2.** Downstream channel hierarchy.

All bandwidth management and MAC layer management messages are packed into ATM cells with preassigned ATM header. Request bandwidth allocation plays important role in beginning the transmission process. The overall MAC operation will be detailed in section 7.3.

7.2.3 Synchronization

As illustrated in section 3.1.1, R_x-R_a here refers to round trip correction (RTC) which is used to delay a station's upstream timing relative to its downstream timing. Figure 7-1 shows how the RTC value is calculated for a given station.



■ **Figure 7-1**. Calculating the round trip correction.

At time 150, the headend transmits an INVITATION. This message contains the headend's current time. Thirty time units later, a newly attaching station receives the INVITATION and sets its local time to 150. After waiting a variable amount of time, in this case 20 time units, the station transmits an INVITATION_RESPONSE. This response indicates the station's current local time, namely 170. When the headend receives the INVITATION_RESPONSE at time T=250, the headend will immediately subtract its current time from the time found in the response. This value is the round trip delay to this particular station and is equal to 250-170=80 time units. Assuming that the maximum round trip time, to the most distance station, is 100 time units, the RTC value is 100-80=20 time units. An ASSIGN_PARAMETERS message is transmitted to the station and the station uses the RTC for future transmission.

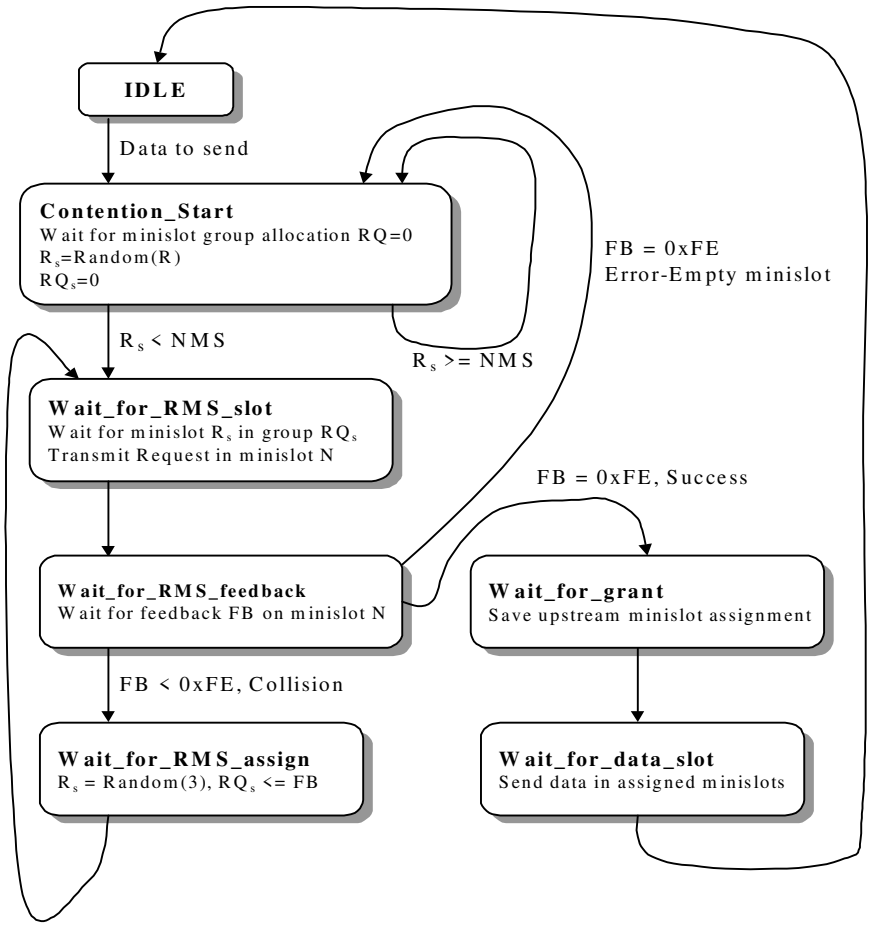
7.2.4 Contention Resolution

Section 7.2.2.2 mentioned that request minislot allocation plays an important role in starting the transmission process. Now we examine how it works. The format of a request minislot allocation is shown in Figure 7-2.

0x04	ELEN	CIL	R	SMS	Group 1	Group 2	. . .	Group n

■ **Figure 7-2**. Request minislot allocation message.

R implies entry persistence. For stations entering the contention process, the entry persistence specifies the probability that the station will contend for access. SMS gives number of the first minislot belonging to this contention cluster. Repeating minislot groups is used to implement the 3-ary tree collision resolution algorithm. Each group contains RQ (request queue) and NMS (number of minislots). A group with RQ field of zero indicates minislots that new stations may use to enter the contention process. Figure 7-3 details this



algorithm.

■ **Figure 7-3.** Collision resolution state diagram.

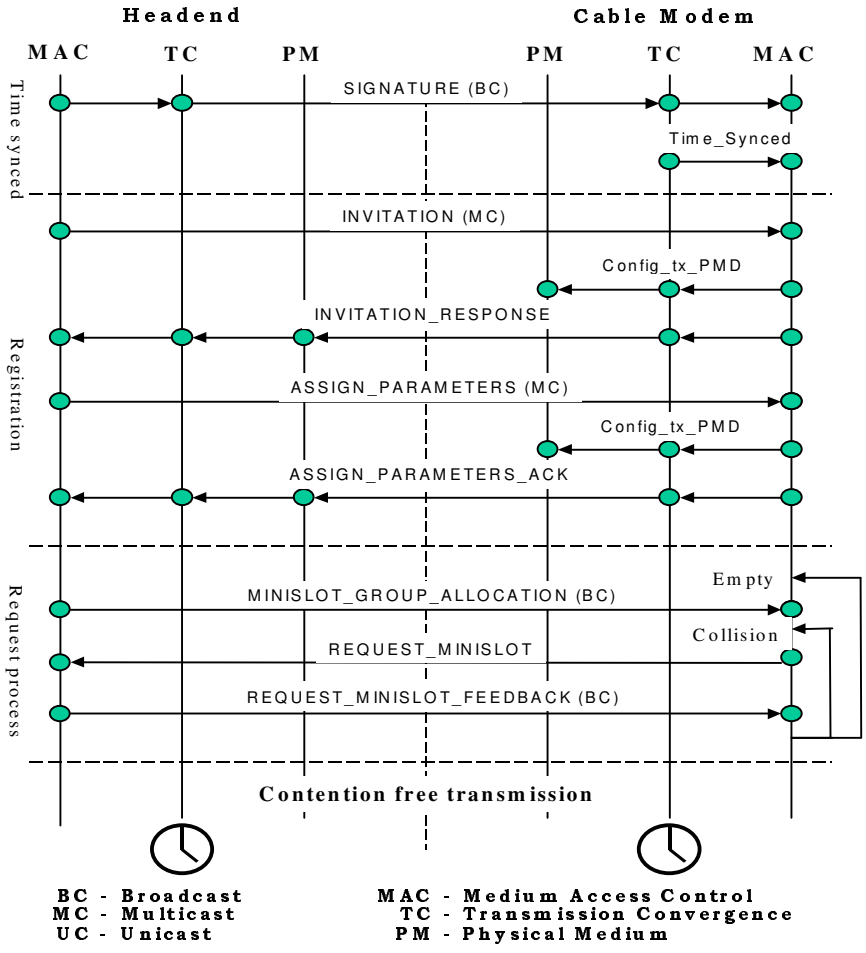
When a station enters the contention process, it waits for a request minislot allocation message that contains a minislot group with an RQ value of zero. Upon receiving such message, the station calculates a random value R_s between zero and R. If this R_s<NMS for the minislot group with RQ value of zero then the station transmits a request PDU in the minislot at position R_s within that group. If the value R_s >= NMS then the station waits for the next opportunity to enter the contention process.

After transmitting the request PDU, the station waits for a request minislot contention feedback. If the feedback indicates that the minislot was empty then the station should simply restart the contention process. If the feedback indicates that the minislot contained a valid request, the station may just wait for grant from headend. If no grant message arrives within a specified timeout then the station should restart the contention process. If the station collided with other stations attempting to make a request in the same minislot, the feedback will indicate that a collision occurred and give a new RQ value to the station. The station then waits for a minislot group with specified RQ value and contends within that group by picking one of the three minislots at random. This process is repeated until the station receives an indication that it made a successful request.

7.3 MAC Operation

From figure 7-4, the MAC operation may separate into four parts. Time synchronization between headend and stations is accomplished in the first part. To achieve time synchronization, PHY lock (modulation lock) and MAC lock (packet lock) are essential. During catching the signature cells, the MAC

instructs the PHY to lock the signal through PHY_Modulation_Lock( ). Once a modulation lock is acquired, TC is required to establish packet sync using TC_Packet_Sync( ). The timeout from PHY_Modulaton_Lock( ) to TC_Packet_Sync( ) is .25 seconds. If synchronization process within one channel failed, the MAC will direct the PHY to tune to next channel. After successfully catching a signature cell, the station set its current local time to the time specified in the time stamp field of that cell and thus the station is in sync with headend.



■ **Figure 7-4.** Timeline of MAC operation.

Parameters exchange are performed in the second part. Headend invites stations through INVITATION message. Unregistered stations may return their

MAC addresses, PHY parameters and current local times using INVITATION_RESPONSE messages. After examining these messages, headend calculates individual RTCs and then passes these values together with PHY adjustments and local identifiers to individual stations through ASSIGN_PARAMETERS messages. Therefore registration process is finished. The third part refers to request process. The contention resolution described in previous section is performed to coordinate of request minislot. The last part is contention free transmission. Piggy-back requests are introduced to fulfill this mechanism.

7.4 Open Technical Issues

There are some technical issues defer to the implementers. First of all is that the algorithm for allocating and deallocating multicast LIs. Secondly, the criteria that allocates cell and variable length fragments bandwidth under fairness consideration. There are also many research topics within 802.14 network. For example, parameters tuning of request minislot allocation under the cooperation between p-persistent and Q-ary algorithm.

8. Conclusions and Future Works

We have proposed a MAC protocol, PCUP, for IEEE 802.14 network. It provides integrated broadband services to the home and supports QoS for various types of traffic. Performance is achieved due to several features. 1) A membership control is done periodically to update the set of on-line stations and the channel usage status. 2) We can neutralize stations' propagation offsets by synchronizing them. The synchronization process, sorting the on-line stations according to their propagation offsets from the headend. 3) An efficient transmission scheduling algorithm is used, in each cycle, to schedule the transmission starting time and duration of each station so that cells appear to be pipelined, i.e. back-to-back, at the headend.

Although the IEEE802.14 standard will be defined well, there are still some open technical issues, as illustrated in section 7.4, defer to implementers. One interesting observation is that is the 3-ary collision resolution algorithm workable while cooperated with p-persistence algorithm? In other word, should we try another parameter other than 3 under different allocation of request minislots? Implementation of one 802.14 network needs tremendous efforts, so only small scale emulation is feasible to be finished by lab work.

9. References

[1] Vijay K. Bhagavath, "*Open Technical Issues in Provisioning High-Speed Interactive Data Services Over Residential Access Networks.*", IEEE Network Magazine, Jan. 1997, pp.10-12.

[2] Chatschik Bisdikian, Kiyoshi Maruyama, David I. Seidman, and Dimitrios N. Serpanos, "*Cable Access Beyond the Hype: On Residential Broadband Data Service over HFC Networks.*", IEEE Communication Magazine, Nov. 1996, pp. 128-135.

[3] John W. Eng, James F. Mollenauer, "*IEEE Project 802.14 : Standards for Digital Convergence.*", IEEE Communication Magazine, May 1995, pp. 20-23.

[4] Leif Aarthun Ims, Dagfinn Myhrem and borgar Torre Olsen, "*Economics of Residential Broadband Access Network Technology and Strategies.*", IEEE Network Magazine, Jan. 1997. pp. 51-57.

[5] William Pugh, Gerald Boyer, "*Broadband Access : Comparing Alternatives.*", IEEE Communication Magazine, Aug. 1995, pp. 34-46.

[6] Kim Maxwell, "*Asymmetric Digital Subscriber Line : Interim Technology for the Next Forty Years.*", IEEE Communication Magazine, Oct. 1996, pp. 100-106.

[7] Marlis Humphrey, John Freeman, "*How xDSL Supports Broadband Services to the Home.*", IEEE Network Magazine, Jan. 1997, pp. 14-23.

[8] Bhumip Khasnabish, "*Broadband to the Home (BTTH) : Architectures, Access Methods, and the Appetite for It.*", IEEE Network Magazine, Jan. 1997, pp. 58-69,

[9] Charles A. Eldering, Nageen Himayat, and Floyd M. Gardner, "*CATV Return Path Characterization for Reliable Communications.*", IEEE Communication Magazine, Aug. 1995, pp. 62-69.

[10] Chatschik Bisdikian, "*MLAP : A MAC Level Access Protocol for the HFC 802.14 Network.*", IEEE Communication Magazine, Mar. 1996, pp. 114-121.

[11] James E. Dail, Miguel A. Dajer, Chia-Chang Li, Peter D. Magill, Curtis A. Siller, Jr., Kotikalapudi Sriram, and Norman A. Whitaker, "*Adaptive Digital Access Protocol : A MAC Protocol for Multiservice Broadband Access Networks.*", IEEE Communication Magazine, Mar. 1996, pp. 104-112.

[12] Morihisa MOMONA, Shuntaro YAMAZAKI, "*Framed Pipeline Polling for Cable TV Networks.*", presented at IEEE802.14 Interim Meeting (95/01, Andover).

[13] Chris Grobicki, John M. Ulm, "*UniLINK as Media Access Protocol for Comminity Cable TV.*", proposed by LANcity corp.

[14] Ying-Dar Lin, Chia-Jen Wu, and Wei-Ming Yin, "*PCUP : Pipelined Cyclic Upstream Protocol Over Hybrid Fiber Coax.*", IEEE Network Magazine, Jan. 1997, pp. 24-34.

[15] IEEE 802.14 Working Group, "*Performance Evaluation Process for MAC Protocols*.", IEEE802.14/95-061R3(phase 1).

[16] Tho Le-Ngoc, S. V. Krishnamurthy, "*Performance of Combined Free/Demand Assignment Multiple-Access Scheme in Satellite Communications*.", International Journal of Satellite Communications, Vol. 14, 1996, pp. 11-21.

[17] Kleinrock, "*Queueing Systems, Volume I : Theory*.", pp. 19-43.

[18] IEEE 802.14 Working Group, "*Media Access and Control*", draft supplement to IEEE Std 802.14.

[19] IEEE 802.14 Working Group, "*Physical Layer Specification for HFC CATV Networks*", draft supplement to IEEE Std 802.14.

[20] Ray Zeisz, "*Formal Proposal for 802.14 MAC Protocol (Part 1 of 2) : MLMP (MAC Level Management Protocol)*", IEEE802.14-95/157, draft proposal.

[21] Bill McNeil, Rob Norman, "*Formal Proposal for 802.14 MAC Protocol (Part 2 of 2) : MLAP (MAC Level Access Protocol)*", IEEE802.14-95/158.