# PCUP: Pipelined Cyclic Upstream Protocol Over Hybrid Fiber Coax

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## Abstract

In order to bring NII (National Information Infrastructure) into the home, the community cable TV networks have to be reengineered to support two-way interactive services. In this work, the authors propose PCUP (Pipelined Cyclic Upstream Protocol) as the upstream MAC (medium access control) protocol for HFC (hybrid fiber coax) community access network. PCUP 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 a transmission starting time and duration in a cycle. By taking into account the propagation offsets and 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, which runs a contention-based tree walk algorithm, is executed periodically to allow the stations to join or leave. The authors also compare PCUP with various schemes proposed to IEEE 802.14 committee.

With NII (National Information Infrastructure) plans being executed in many countries since 1993,CATV (cable TV) is getting more conspicuous. First, the telecommunication competition and deregulation actions are ongoing all over the world [1, 2]. Second, with the outstanding throughput, popularity, and inexpensive replacement of existing in-home wiring, more and more companies are adopting the cable network to offer full broadband services [1, 3–5]. Cable companies have become the leading players in the search for ways to expand the aynchronous transfer mode (ATM)-based NII backbone network into the home [1, 4, 5]. However, the community networks must support two-way asymmetric traffic patterns and arbitrate multiple accesses for available bandwidth.

HFC (hybrid fiber coax) [6, 7] is gradually becoming the standard for many cable companies. We address the challenge of data communication over HFC and propose a suitable MAC-layer protocol upstream for HFC.

Figure 1 represents a piece of an HFC system. Clusters of homes, 500 to 2000 subscribers, are served by a fiber that comes from the headend. The signal is distributed to homes within the serving area of a fiber node via an amplified tree-and-branch feeder cable, perhaps as short as 3 mi in total length. Each branch serves 125 to 500 subscribers. One of the limitations here is that the station cannot listen directly to the upstream transmissions from other stations; hence, they are incapable of detecting collisions and coordinating their transmissions all by themselves. A multiple access technology other than carrier sensing is required so that all subscribers within a branch can share the available reverse bandwidth.

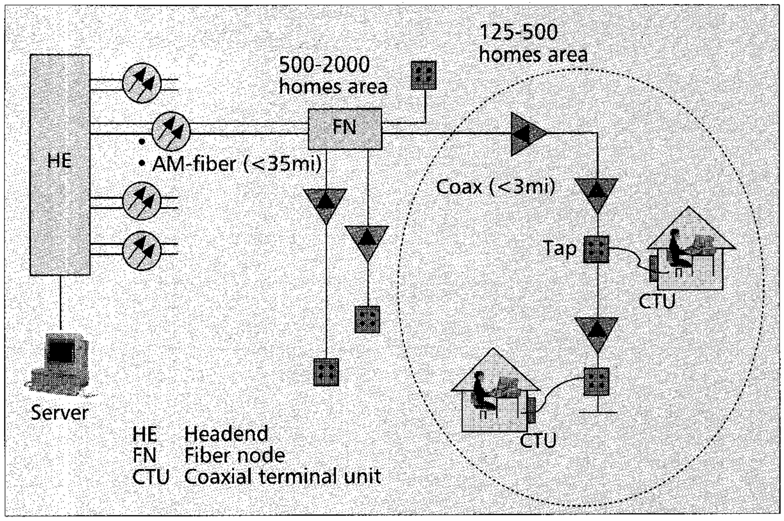
In practice, the analog band from a station to its headend is relatively narrow and of poor quality. In the downstream direction, channel bandwidth is more abundant with less noise. A typical frequency spectrum for the subscribers to use is given in Fig. 2. Assume a total bandwidth of at least 800 MHz available on all the coaxial cable links. A 400 MHz band, from 150 MHz to 550 MHz, may be used to carry conventional analog broadcast 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 Mb/s [7]. These upstream channels are called *"multi-access channels"* and used to carry signaling and data. A larger downstream bandwidth, 70 to 130 MHz, is used as the downstream counterpart for those upstream multi-access channels. Other constant bit rate services, such as voice and video telephony, use 27 MHz to 54 MHz upstream and 750 MHz to 800MHz downstream.

It is the upstream multi-access channel that this article

*This work was supported in part by National Science Council, Taiwan, and Mentor Data System Inc., Hsinchu Science-based Industrial Park, Taiwan, under a joint project, NSC85-2622-E-009-006R.*

addresses. The rest of the article is organized as follows. In the second section, we survey and compare the proposed MAC schemes. Two schemes, one distributed R-ALOHA and one centralized UniLINK, are described in detail and selected for later numerical comparison with our scheme. Our PCUP (Pipelined Cyclic Upstream Protocol) is presented in the third section, where protocol mechanisms and messages are defined. The fourth section evaluates PCUP and compares it with R-ALOHA and UniLINK. Finally, the last section concludes the article.




■ Figure 1. *The architecture of HFC. Subscribers in the feeder cable can only listen to the downstream for the headend and transmit in the allocated upstream.*

## MAC Alternatives

The main goal of the IEEE 802.14 Cable TV LAN MAC/PHY committee is to provide interactive multimedia services over HFC networks. To meet this target, the MAC protocol should satisfy the following requirements:

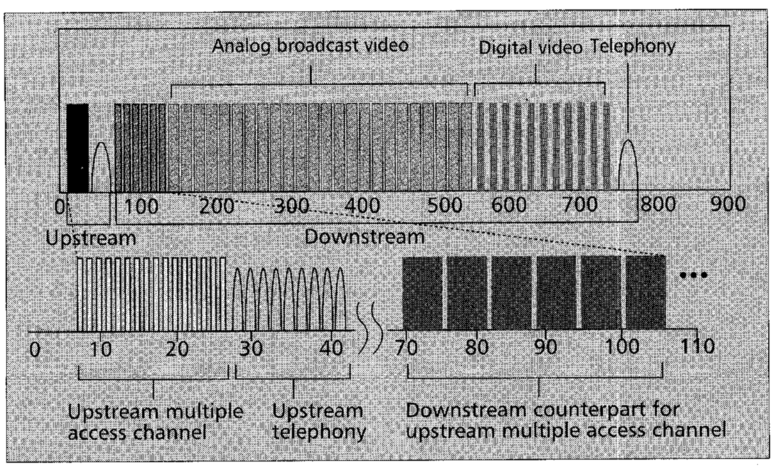
- Dynamic bandwidth allocation to CBR (constant bit rate), VBR (variable bit rate) and ABR (available bit rate) traffic types
- High channel throughput
- Low access delay
- Support for a large number of stations
- Metropolitan area coverage

Many MAC protocols have been proposed and studied. They can be classified into two categories: distributed and centralized protocols. There is no central controller in distributed protocols, like carrier sense multiple access with collision detection (CSMA/CD) and R-ALOHA protocols. The centralized protocols provide better timing mechanisms in avoiding collisions. This kind of protocol, proposed by many organizations, include MLAP(MAC Level Access Protocol) of IBM Corp. [22], XDQRAP(Extended Distributed Queuing Random Access Protocol) of Scientific-Atlanta, Inc. [23], ADAPt (Adaptive Digital Access Protocol) of AT&T Bell Laboratories [21], UniLINK protocol of LANcity Corp. [17], FPP(Framed Pipeline Polling) protocol of NEC corp. [19], CPR (Centralized Priority Reservation) protocol of Georgia Institute of Technology [20], traditional TDMA (time-division multiple access), and others. We also present our CATV MAC protocol, PCUP, which will be described in more detail in the next section.

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 [22]. FPP works similarly, except the station transmits its data immediately after the headend polls it [19]. In the CPR protocol, a station sends a request to the headend using a contention channel. The headend acknowledges the request and then schedules the request in a first come first served (FCFS) fashion, informing the station by means of a grant message about when to transmit [20]. XDQRAP works similarly to CPR. It also provides an immediate transmission mode, allowing a single cell message to be transmitted without requests [23]. 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. The contention bandwidth is randomly accessed [17, 21].

In order to characterize these protocols, we make a comparison in Table 1. The entry of scheduling discipline means how connections' bandwidth requests are processed. These requests are either granted in an FCFS fashion or fairly allocated at the end of a cycle.

From Table 1, we see that conventional MAC protocols cannot meet the multimedia requirements. For example, the CSMA/CD protocol cannot support isochronous traffic due to its random access control. Furthermore, direct implementation of CSMA/CD over HFC is not possible since stations cannot sense the upstream transmission. The headend has to mirror the upstream transmission to the downstream channel. In contrast, TDMA can support isochronous traffic. However, since it has poor flexibility in bandwidth allocation, it cannot support bursty traffic efficiently. Although R-ALOHA can handle bursty traffic, it has the problem of unfairness and no quality of service (QoS). In order to satisfy QoS requirements, centralized protocols with hybrid bandwidth allocation mechanism are more feasible. Although ADAPt and UniLINK protocols are centralized and hybrid, contention-based band-




■ Figure 2. *Spectrum allocation of HFC. In the downstream, some bandwidth is reserved for urgency air rescue or marked as unusable by some preliminary trials in [8].*

| | CSMA/CD | R-ALOHA | MLAP | XDQRAP | ADAPt | UniLINK | CPR | FPP | PCUP |
|---|---|---|---|---|---|---|---|---|---|
| Distributed | √ | √ | | | | | | | |
| Centralized | | | √ | √ | √ | √ | √ | √ | √ |
| Isochronous bandwidth | | | | | √ | √ | | | |
| Reservation bandwidth | | √ | √ | √ | √ | √ | √ | √ | √ |
| Contention bandwidth | √ | √ | | √ | √ | √ | | | |
| Scheduling discipline | N/A | N/A | Fair scheduling | FCFS | FCFS | FCFS | FCFS | Fair scheduling | Fair scheduling |
| QoS | | | √ | √ | √ | √ | √ | √ | √ |
| Timing implemented by | H/E | H/E | H/E STU | H/E | H/E | H/E STU | H/E | H/E STU | H/E |
| Headend complexity | ■ | ■■ | ■■■■ | ■■■■ | ■■■■ | ■■■■ | ■■■ | ■■■■ | ■■■ |
| Station complexity | ■ | ■ | ■■ | ■■ | ■ | ■■ | ■■ | ■■ | ■ |
| | | N/A = not applied | | H/E = headend | | STU = set-top unit | | | |

■ Table 1. *Features comparison of proposed MAC protocols.*

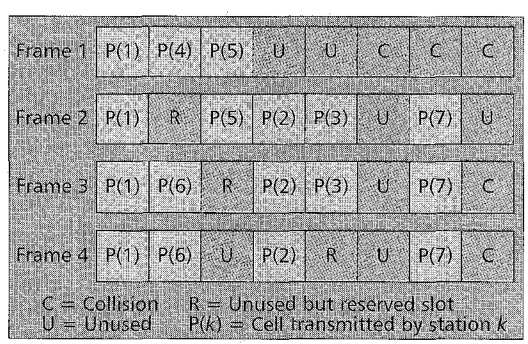
width will be the bottleneck of throughput under heavy best-effort traffic.

We also see that PCUP, FPP, and MLAP protocols behave in a similar way. They gather all bandwidth requests and schedule them together. Among these three, something different can be observed. In MLAP protocol, the headend uses the $n$-ary Stack Resolution (START-$n$) algorithm to ensure that a station can transmit in a chain of contention-free transmissions for a long message. In the FPP protocol, the headend may poll every station three times for CBR, VBR, and ABR traffic types in a frame. This intensive polling increases the headend processing load. Another difference between FPP and PCUP is that in an FPP frame, a station transmits its CBR, VBR, and ABR traffic in three different regions, while in a PCUP frame, a station transmits these three consecutively. Furthermore, delay adjustment, which is also called positioning or ranging, is done by stations in both the MLAP and FPP protocols. This adds to the station complexity. In the CPR protocol, there are two factors that limit performance. First, all bandwidth requests are contention-based. This scheme will lead to unfairness between stations and throughput degradation under heavy traffic. Second, an individual station must wait one round-trip delay before sending each message [20]. Given these observations, PCUP stands out in various aspects. Before describing the PCUP protocol, two typical protocols, one distributed and one centralized, are examined. They are compared numerically with PCUP later. The R-ALOHA protocol is distributed with a bandwidth reservation scheme, and UniLINK is centralized with a hybrid bandwidth allocation scheme.

## *Distributed Protocol: R-ALOHA [14]*

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:

- Idle, which means it is empty
- Collision, which means two or more cells are transmitted into it, and thus none could be received correctly
- Success, which means exactly one cell is transmitted into it and successfully received.




■ Figure 3. *Implicit reservation scheme.*

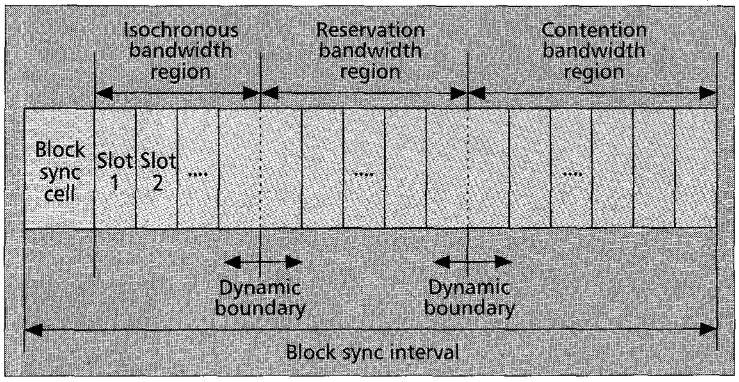
The network operates without any central control, but requires each station to obey the same set of rules depending on what happened in the previous frame. Successful transmission in a slot serves as a *reservation* for the corresponding slot in the next frame. By repeated use of that slot position, 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 the Slotted ALOHA protocol. The reservation scheme is illustrated in Fig. 3 [18].

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 might happen.

## *Centralized Protocol: UniLINK [17]*

The UniLINK protocol has been designed to operate within the community-wide HFC infrastructure. It is based on 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 Fig. 4.

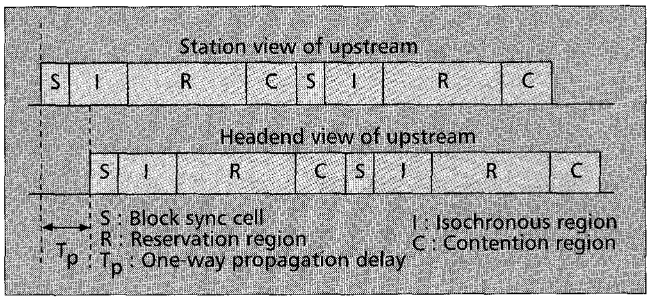
The isochronous assignment is the static allocation of slots to a particular station. This allows UniLINK to support applications that require fixed, guaranteed, jitter-free bandwidth. CBR service is suitable for this region. Reservation assignment is reservation-based and granted as needed. These slots 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 applications with bursty traffic such as VBR service. The contention region is available to all other traffic with a probability of collision and behaves similar to Slotted ALOHA.




■ Figure 4. *Dynamic allocation of bandwidth.*

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. If it wishes to transmit in a slot, it simply starts the transmission early by the amount of its own one-way propagation delay to make it arrive at the exact time desired. Figure 5 shows the upstream block sync interval timing relationship between headend and stations.

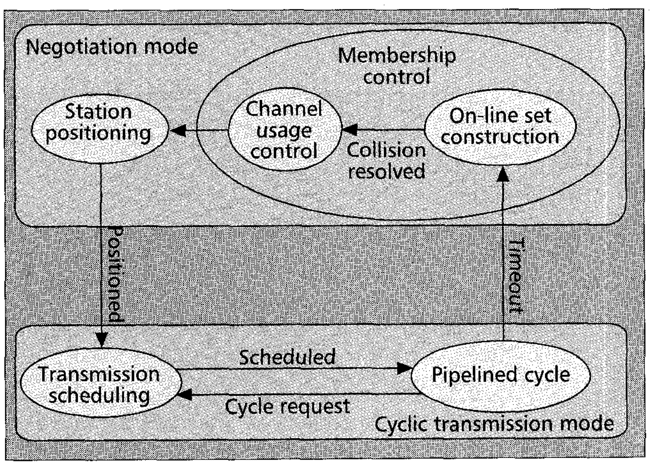



■ Figure 5. *Timing relationship in upstream block sync interval.*

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 and fairness may not be guaranteed.

## PCUP (Pipelined Cyclic Upstream Protocol)

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




■ Figure 6. *State transition diagram of the headend in PCUP operations.*

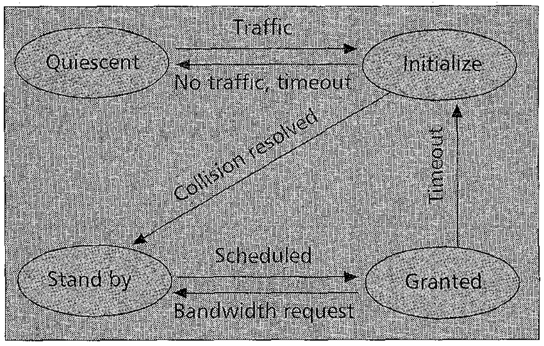
### Overall System Description

*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.

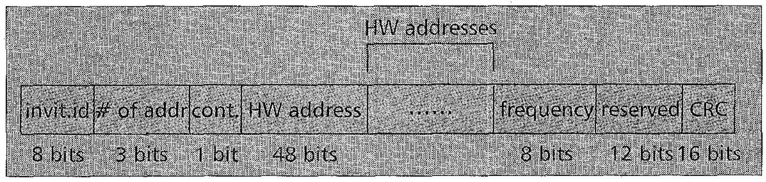
We divide PCUP operations into two transmission modes: cyclic transmission mode and negotiation mode (Fig. 6). In Fig. 6 the condition to switch between the modes is triggered by a timer. PCUP runs a tree walk contention-based algorithm of the membership control in the negotiation mode so that stations 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 a station's propagation offset so that cells arrive at the headend as though they were sent with zero propagation delay.

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




■ Figure 7. *State transition diagram of stations in PCUP operations. The initialize state includes station positioning and cycle membership control. Note that standby corresponds to transmission scheduling, and granted corresponds to the pipelined cycle in the headend state transition diagram.*




■ Figure 8. *Thre frame structure of* `HE.invitation`*. It is used in the membership control to invite the off-line stations to be on-line.*

| Entry name | Descriptions |
|---|---|
| `invit-id/freq-id/pos-id/alloc-id` | All the `*-ids` in control frames are used for the subscribers to perform achnowledgment |
| `logical ID` | This is the 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 2. *Description of symbols.*

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 Fig. 7.

*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 Figs. 8–11, and summarize some variables used in these frames in Table 2. A `Request_Table` is maintained in the headend to monitor the whole system. The included fields of the `Request_Table` are shown in Table 3.

## Membership Control

In the negotiation mode, the headend has to do the following:

- Reconstruct the set of on-line stations
- Position the on-line stations into a sequence
- Balance the usage of all upstream channels to alleviate the competition

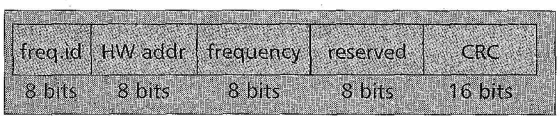
Our membership control deals with the first and third tasks.

*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 s or more. The headend issues an `HE.invitation frame`, as shown in Fig. 8, to the stations that do not belong to the set (i.e., not in `Request_Table`)[1] and starts a tree walk algorithm [9] to update the set of on-line stations. On-line stations that 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 something, will still be on-line with no need to send them the `HE.invitation` frame.

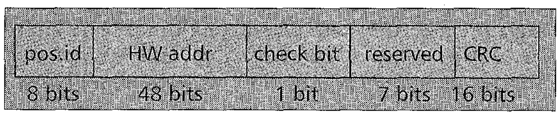
`HE.invitation` contains multiple hardware addresses. The field `num_addr` indicates the number of hardware addresses contained in the frame, while `cont bit` indicates whether this control frame extends to the next cell. Careful readers may find that the total length of these fields is 384 bits, which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

*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 upstream is necessary in order to balance the channel utilization.

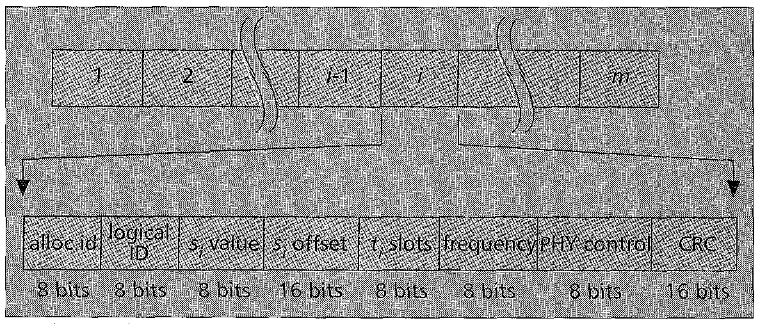
[1] *Because the tree walk algorithm is time-consuming, invitation procedure only invites those that are not the current on-line stations.*




■ Figure 9. *The frame structure of* `HE.balance`*. It is used in the membership control to balance the channel utilization.*




■ Figure 10. *The frame structure of* `HE.position`*. It is used in the station positioning to measure the propagation offset from the headend.*




■ Figure 11. *The frame structure of* `HE.schedule`*. The frame is composed of* m *items, where* m *is the number of the on-line stations. It is used in the transmission scheduling to allocate the transmission starting time and duration computed by the headend.*

| Attribute | Descriptions | Size |
|---|---|---|
| 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 frame | 8 |
| 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. *Request_Table.*

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 rearranged stations to notify them to which channels to switch.

Pseudo code for headend and station in Fig. 12 summarizes the operations of cycle membership control, which includes online 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 12. *Pseudo code for cycle membership control.*

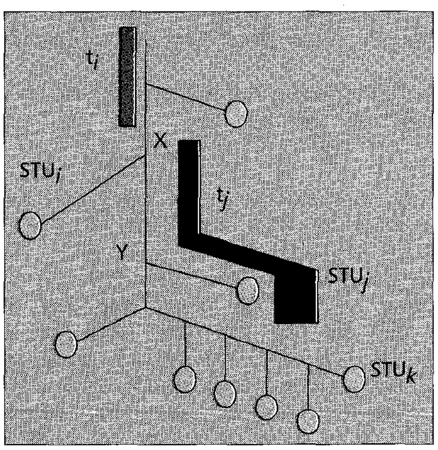
## *Station Positioning*

One uniqueness of HFC is that stations cannot listen directly to the upstream transmissions from other stations; hence, they are incapable of detecting collisions and coordinating their transmissions all by themselves. What they can do is to listen and transmit on the allocated downstream and upstream, respectively.

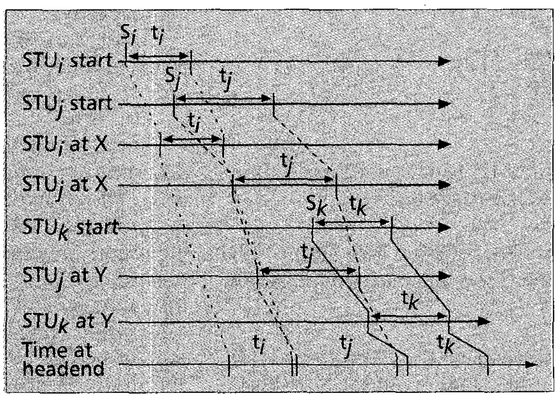
Our station positioning is the key to coordinating the stations' transmissions. It aims to neutralize a station's propagation offset so that cells arrive at the headend as though they were sent with zero propagation delay. With the back-to-back transmission at the headend, the upstream channel will perform more efficiency without waste. We explain the scheme by Fig. 13. In Fig. 13, $X$ is the branching point of $STU_i$, and the difference of propagation delays between $X$ to $STU_i$ and $X$ to $STU_j$ is $\tau_{ij}$ ($\tau_{ij} = \tau_{jx} - \tau_{ix}$, where $\tau$ represents propagation delay). We can find out that the ideal situation at $X$ can be modeled as

$$s_i + t_i + G = s_j + \tau_{ij}, \quad (1)$$

where, $s_i$, $i = 1, 2, \ldots N$, 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. The scenario of this ideal situation is described in a clearer way by the timeline in Fig. 14. It is obvious that the headend needs to position the stations correctly in order to schedule transmissions in this way.




■ Figure 13. *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 14. *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 the headend. The headend sends a HE.position frame (shown in Fig. 10) 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, by either hardware or firmware. Headend computes the *distance* from the headend to the station as

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

where $t_{rec}$ is the time the headend receives the returned HE.position, $t_{tx}$ is the time headend transmits HE.position, $t_{\text{overhead}}$ is the transmission delay and possible processing delay, and $c$ is the signal propagation speed. A 16-bit timing counter with units of 61 ns is sufficient for the CATV length specified by [10]. The headend sorts these stations in

```
FOR (all on-line STU)
 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 (2)
sort STUs by distance
```

■ Figure 15. *Pseudo code of station positioning.*

increasing order of distance. The station positioning algorithm is summarized in Fig. 15.

### 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, at the end of its transmission duration.

Requests have two priority levels in PCUP: best-effort and guaranteed. Slots are allocated according to the reported requests. Even if an empty buffer is reported, the headend allocates one slot to the station so 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 allocates a proper number of slots according to the traffic urgency parameters ($\alpha_i$ and $\beta_i$). The headend allocates transmission quota, $t_i$, for station $i$, as follows:

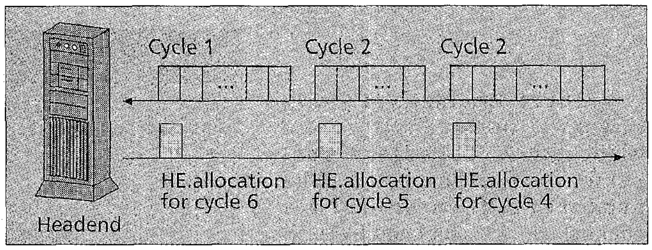
$$t_i = \begin{cases} (1)\ \text{if } \sum(b_i + W_i) < CBT \\ \quad \max(b_i, 1) + W_i, \\ (2)\ \text{if } \sum(b_i + W_i) > CBT \\ \quad \max(CBT \times \frac{\beta_i}{\sum \beta_i}, 1) + W_i, \\ (3)\ \text{if } \sum(G_i + b_i + W_i) < CBT \\ \quad \max(G_i + b_i, 1) + W_i, \\ (4)\ \text{if } \sum(g_i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

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. The sum of all best-effort requests does not exceed the link capacity; thus, all can be served.

*Case (2)* — There is only best-effort traffic. The sum of all best-effort requests exceeds the link capacity; thus, these best-effort cells are served partially and proportionally according to their urgency parameters, $\beta_i$.

*Case (3)* — The sum of all best-effort and guaranteed services does not exceed the link capacity; thus, all can be served.




■ Figure 16. *Look-ahead allocation.*

```
CASE (HE.schedule received)
 transmit cells in allocated time slots
 report 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 17. *Pseudo code of station operations.*

```
IF (time up of Group_Reset_Timer)
 cycle membership control (in Fig. 12)
 station positioning (in Fig. 15)
ELSE
 seize a cell from input buffer
 process the cell, upgrade Request_Table, ack to station
 issue HE. schedule frame (in Fig. 11) if all the on-line stations'
  requests are collected
```

■ Figure 18. *Pseudo code of headend operations.*

*Case (4)* — The sum of all best-effort cells and minimum guaranteed cells can be served. The leftover capacity is used to serve as many, up to $G_i - g_i$ for station $i$, guaranteed cells as possible.

*Case (5)* — The sum 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-effort cells are served partially according to their urgency parameters, $\beta_i$. $\beta_i$ is used as the weight of station $i$ in distributing the leftover capacity.

*Case (6)* — This case is the worst situation, where the link capacity is less than the sum of minimum guaranteed services. Thus, the guaranteed cells are served partially by their urgency parameters, $\alpha_i$. $\alpha_i$, 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:

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

Then, the 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 Fig. 11.

Note that with the possible long propagation delay, the headend may need to preallocate the `HE.schedule` frame several cycles ahead, as illustrated in Fig. 16. The amount of this look-ahead has to be longer 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.

### Summary of PCUP

We now summarize the PCUP operations in Figs. 17 and 18. The pseudo code includes station and headend operations.

| Fields | Descriptions | Size (bytes) |
|---|---|---|
| $b_i$ | Number of best-effort cells at $STU_i$ | 2 |
| $g_i/G_i$ | Minimum/requested number of guaranteed cells at $STU_i$ | 2/2 |
| $\alpha_i/\beta_i$ | Urgency of guaranteed/best-effort cells at $STU_i$ | 1/1 |

■ Table 4. *Station slot requests, appended in the final slot of its transmission.*

## Simulation Study

We show the numerical results in this section regarding loss ratio, throughput, access delay, cell delay variance, and fairness. We first examine the HFC network configuration and traffic models, followed by the simulation results of R-ALOHA [11, 13, 14], UniLINK [17], and PCUP.

### Network Configuration

We assume the values of some configuration parameters based on the existing proposals [6, 7, 10, 15]:

- 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 Mb/s to 10 Mb/s in capacity. According to [7], we assume the upstream frequency range to be 8–26.5 MHz and 1.544, 2.048, 6, and 10 Mb/s 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 Mb/s 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 with several branches. Each branch serves 125 to 500 homes, which means an upstream channel is shared by about 30, 35, 100, and 167 subscribers, respectively. The scale of the network is assumed to be 80 km.

### Traffic Models

Three types of traffic models are applied in the simulations.

*Traffic Model A: All Best-Effort ABR (Available Bit Rate)[16]* — The first traffic model contains only LAN like traffic, e-mail, file transfer, and so on, to demonstrate the protocol's capability to support the existing data services. Poisson is assumed to be the traffic source model.

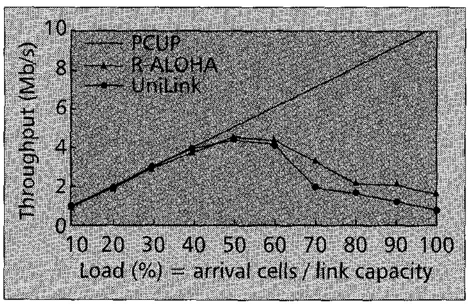
*Traffic Model B: ABR and CBR (Constant Bit Rate) Services* — CBR applications contribute 50 percent traffic load; 50 percent remains ABR. The PCR (peak cell rate) [16] generated by a common CBR telephony application is 64 kb/s. This model can test the stability of the MAC protocols.

*Traffic Model C: ABR, CBR, and VBR (Variable Bit Rate) Services* — VBR applications present 30 percent of traffic, CBR 30 percent, 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 QoS of the ABR applications under the heavy traffic presented by the VBR and CBR applications.

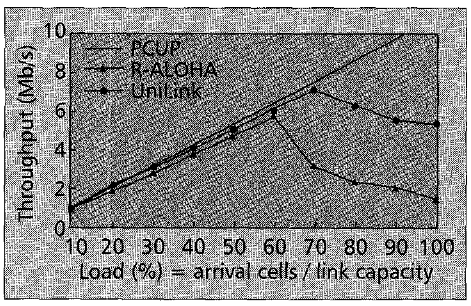
### Numerical Results

*System Throughput* — In Figs. 19–21, 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 for 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 percent. The 1.62 percent left over is due to the 2 μs guard-band time we put and a fraction of slot time that is not enough for a complete slot within the whole cycle.

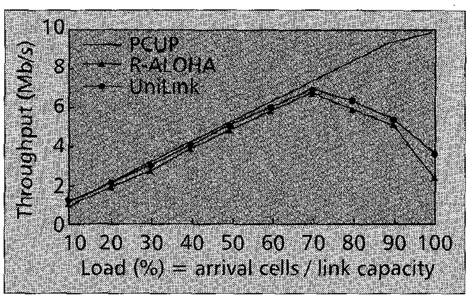
In Fig. 22, PCUP obtains higher throughput than the R-ALOHA and UniLINK no matter what the channel capacity is. At 1.544 Mb/s channel bandwidth and 90 percent traffic load, PCUP has throughput 15 percent higher than UniLINK's, while at 10 Mb/s channel bandwidth and the same traffic load, PCUP has throughput 37.6 percent higher than UniLINK's. UniLINK performs worse than PCUP due to the effect of contention bandwidth, but it works better than



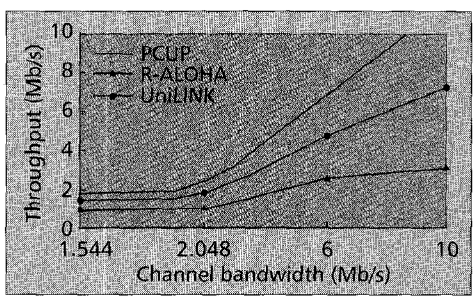

■ Figure 19. *Throughput of PCUP, R-ALOHA, and UniLINK under traffic model A. The channel capacity is 10 Mb/s.*



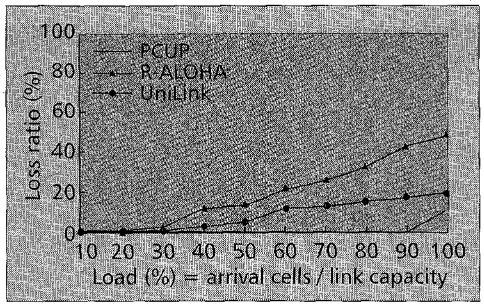

■ Figure 20. *Throughput of PCUP, R-ALOHA, and UniLINK under traffic model B. The channel capacity is 10 Mb/s.*



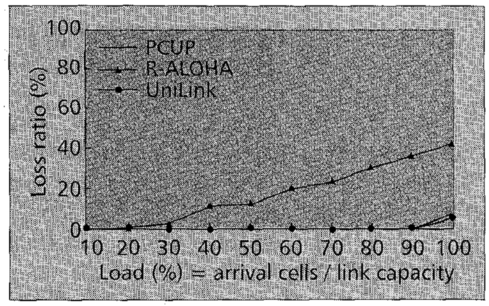

■ Figure 21. *Throughput of PCUP, R-ALOHA, and UniLINK under traffic model C. The channel capacity is 10 Mb/s.*



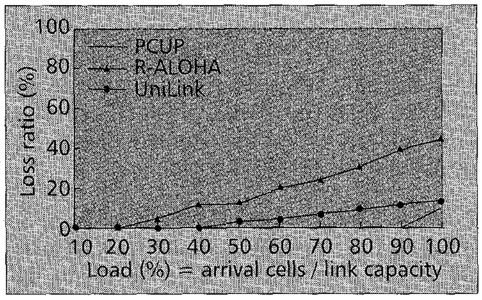

■ Figure 22. *Throughput of PCUP, R-ALOHA, and UniLINK under different channel capacities. Traffic model C; traffic load 90 percent.*



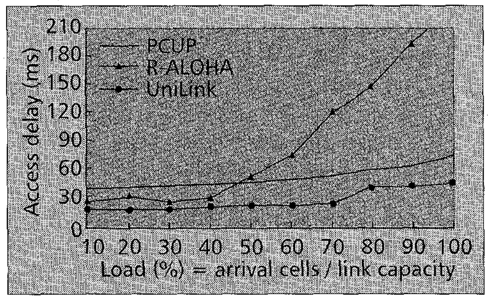

■ Figure 23. *ABR traffic lost ratio of PCUP, R-ALOHA and UniLINK under traffic model C.*




■ Figure 24. *CBR traffic lost ratio of PCUP, R-ALOHA and UniLINK under traffic model C.*




■ Figure 25. *VBR traffic lost ratio of PCUP, R-ALOHA and UniLINK under traffic model C.*



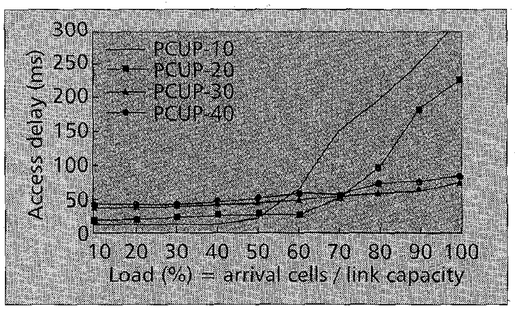

■ Figure 26. *Access delay of PCUP, R-ALOHA, and UniLINK under traffic model A.*

R-ALOHA since it provides isochronous bandwidth assignment and a reservation scheme to support CBR and VBR traffic respectively.

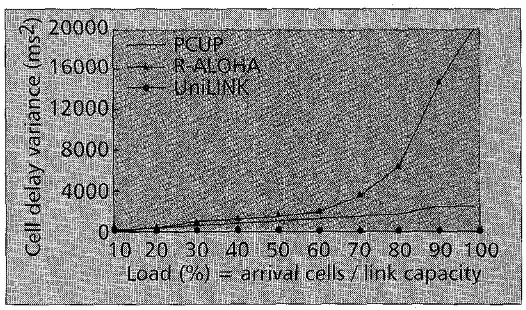
*Loss Ratio* — After examining the numerical result of throughput, we investigate another aspect of channel assignment. Now we focus on the loss ratio, which is defined to be lost cells over arrival cells. From Fig. 23, it is obvious that PCUP does better than R-ALOHA and UniLINK for ABR traffic since R-ALOHA and UniLINK are contention-based in processing ABR traffic requests. In Fig. 24, we find that UniLINK has better performance than PCUP. UniLINK has only 3.1 percent loss ratio when the system is fully loaded, while PCUP has 5.1 percent 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. 25 with Fig. 23, the curves are similar, but UniLINK achieves lower loss ratio of VBR traffic. This scenario is due to applying a reservation scheme over VBR traffic. In R-ALOHA, every cell is treated the same way (i.e., no priority). Thus, it behaves similarly under various traffic types.

*Access Delay* — In Fig. 26, 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 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.

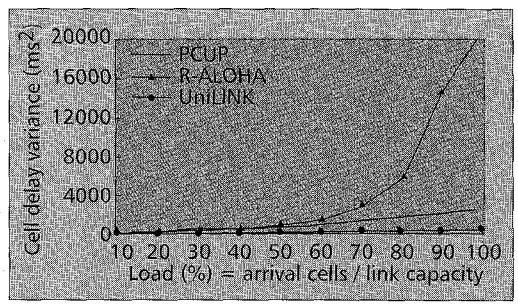
Now we focus on the impact due to the cycle time. In Fig. 27, something interesting can be observed. The access delay increases dramatically under heavy traffic when the cycle



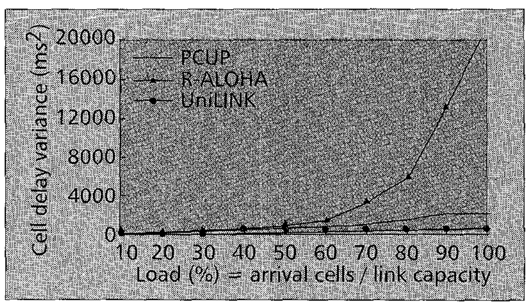

■ Figure 27. *Access delay of PCUP under different cycle times. The traffic model is C, and the channel bandwidth is 10 Mb/s. PCUP-10, for example, means the cycle time is 10 ms.*




■ Figure 28. *ABR traffic cell delay variance (CDV) of PCUP, R-ALOHA and UniLINK under traffic model C. The channel bandwidth is 10 Mb/s.*




■ Figure 29. *CBR traffic cell delay variance (CDV) of PCUP, R-ALOHA, and UniLINK under traffic model C. The channel bandwidth is 10 Mb/s.*



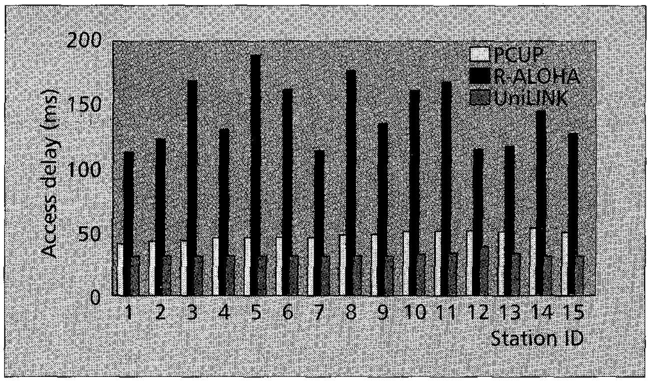

■ Figure 30. *VBR traffic cell delay variance (CDV) of PCUP, R-ALOHA and UniLINK under traffic model C. The channel bandwidth is 10Mb/s.*

time is small. We can explain this scenario by an example. Consider subway systems; there are two alternatives: heavy system and light system. In the heavy system, high-capacity trains operate with longer train interarrival times. In the light system, low-capacity trains operate with shorter train interarrival times. 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 due to its shorter train interarrival time.

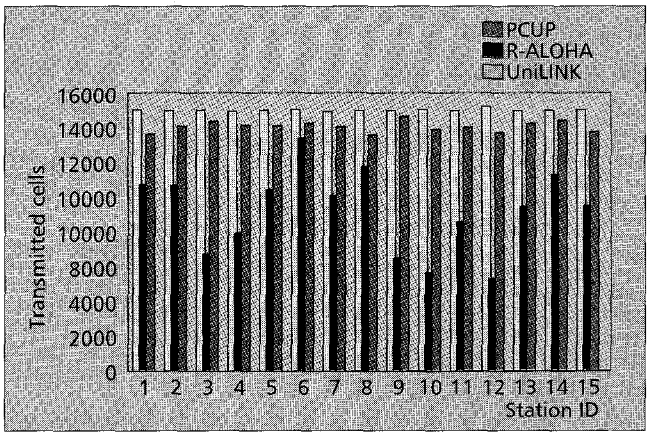
*Cell Delay Variance (CDV)* — CDV is the guideline for examining the jitter performance of the MAC protocol in processing real-time traffic. From Figs. 28–30, R-ALOHA cannot achieve the QoS requirement. This result is due to its random access control and single-priority treatment to all traffic types. 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.

*Fairness* — Fairness is another issue while considering performance of an interactive CATV MAC protocol. In Figs. 31 and 32, 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 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 longer access delay for farther stations and shorter access delay for nearer stations.

From the view point of successfully transmitted cells per station, we see that, in Fig. 32, PCUP performs very well. Because of the FCFS scheduling of bandwidth requests, UniLINK behaves a little unfairly. R-ALOHA still results in starvation at some stations.




■ Figure 31. *Access delay of PCUP, R-ALOHA, and UniLINK under traffic model C. The channel bandwidth is 10 Mb/s and traffic load is 90 percent.*




■ Figure 32. *Successfully transmitted cells of PCUP, R-ALOHA, and UniLINK under traffic model C. The channel bandwidth is 10 Mb/s and traffic load is 90 percent.*

## Conclusions and Future Work

To achieve interactive broadband multimedia service requirements over the HFC network, a MAC protocol with centralized and hybrid bandwidth allocation features is essential. A centralized protocol can fairly schedule the bandwidth and easily synchronize the stations. A hybrid bandwidth allocation MAC protocol can satisfy QoS requirements according to various traffic types. We have proposed a centralized and hybrid MAC protocol, PCUP, for an IEEE 802.14 network. It provides integrated broadband services to the home and supports QoS for various types of traffic. Several features contribute to PCUP's performance:

- Membership control, which periodically updates the set of on-line stations and the channel usage status
- A synchronization process, which neutralizes stations' propagation offsets
- An efficient transmission scheduling algorithm to schedule, in each cycle, the transmission starting time and duration of each station so that cells appear to be pipelined (i.e., back-to-back) at the headend

With station positioning and cyclic scheduling, PCUP achieves a pipelined perfect transmission scheduling, which results in throughput over 98 percent. When the load is below 95 percent, the throughput for PCUP is close to the theoretical bounds and no loss occurs. Concerning the random access protocols under medium to heavy load, retransmitted traffic dominates and results in serious loss, which is not suitable for reliable and delay-sensitive transmission. Starvation in R-ALOHA raises the fairness problem. Although the UniLINK protocol achieves better latency and CDV performance, it obtains lower throughput due to the contention-based transmission of ABR traffic. The higher station complexity also raises STU cost.

The work can be continued by a small-scale emulation. The STU can be replaced by a PC, and the throwback feature can be implemented in firmware. The headend can be replaced by a high-speed computer, at least with the ability of 100 MIPS. We can obtain another set of numerical results from the emulation and compare the emulation results with the simulation results.


### Acknowledgments

The authors would like to express their thanks to Dr. Chein-Hsun Wang at Mentor Data System Inc. (Hsinchu 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 dis-

cussion and suggestion during the course of this work.

## References


[1] Y.-D. Lin and C.-J. Wu, "NII Community Network: Interactive CATV," *Proc. Int'l. Conf. Comp. Sys. Tech. for Industrial Apps. (CSIA)*, Hsinchu, Taiwan, Apr. 1996.

[2] S. Churchill, "Telecommunications Alliances," http://www.teleport.com/ ~comc/cable8.html.

[3] C. Blank, "The FSN Challenge: Large-Scale Interactive Television," *IEEE Comp.*, May 1995, pp. 9–13.

[4] C. Carroll, "Development of Integrated Cable/Telephony in the United Kingdom," *IEEE Commun. Mag.*, Aug. 1995, pp. 48–60.

[5] B. Fryer, "Consumers Take Control," http://www.sgi.com/ion/Spring_95/ Orlando.html.

[6] W. Pugh and G. Boyer, "Broadband Access: Comparing Alternatives," *IEEE Commun. Mag.*, Aug. 1995, pp. 34–46.

[7] Digital Audio Visual Council, "DAVIC 1.0 Specifications Revision 4.0," Sept. 1995.

[8] A. E. Bigras, "Listen Up! Digital Audio Is Canada Cable's Next Step," *Int'l. Cable*, Feb. 1993, pp. 28–34.

[9] W. Stallings, *Handbook of Computer Communications Standards*, vol. 2, 2nd. ed., Howard W. Sams & Company, 1990.

[10] IEEE 802.14, "Cable TV MAC/PHY Protocol Working Group Functional Requirements," Oct. 19, 1994.

[11] F. A. Tobagi, "Multiaccess Protocol in Packet Communication Systems," *IEEE Trans. Commun.*, vol. Com-28, no. 4, Apr. 1980, pp. 468–88.

[12] A. S. Tanenbaum, *Computer Networks*, 3rd ed., Prentice Hall, 1996.

[13] W. R. Crowther *et al.*, "A System for Broadcast Communication: Reservation-ALOHA," *Proc. 6th HICSS*, Univ. Hawaii, Honolulu, Jan. 1973.

[14] S. S. Lam, MEMBER, IEEE, "Packet Broadcast Networks — A Performance Analysis of the R-ALOHA Protocol," *IEEE Trans. Comp.*, vol. C-29, no. 7, July 1980, pp. 596–603.

[15] J. W. Eng and J. F. Mollenauer, "IEEE Project 802.14: Standard for Digital Convergence," *IEEE Commun. Mag.*, May 1995, pp. 20–23.

[16] ATM Forum, *ATM User-Network Interface Specification Version 4.0*, Nov. 1995.

[17] J. M. Ulm, LANcity Corp., "A MAC proposal for 802.14," IEEE 802.14/95-134, draft proposal.


*To achieve interactive broadband multimedia service requirements over the HFC network, a MAC protocol with centralized and hybrid bandwidth allocation features is essential*


[18] W. Stallings, *Data and Computer Communications*, 3rd ed., Macmillan, 1991, pp. 363–65.

[19] M. Momona, and S. Yamazaki "Framed Pipeline Polling for Cable TV Networks," Mar. 1995, IEEE 802.14-96/076, draft proposal.

[20] D. Sala and J. O. Limb, "A Protocol for Efficient Transfer of Data over Fiber/Cable Systems," *Proc. IEEE INFOCOM '96*, pp. 904–11.

[21] J. E. Dail *et al.*, "Adaptive Digital Access Protocol: A MAC Protocol for Multiservice Broadband Access Networks," *IEEE Commun. Mag.*, Mar. 1996, pp. 104–13.

[22] C. Bisdikian *et al.*, "MLAP: A MAC Level Access Protocol for the HFC 802.14 Network," *IEEE Commun. Mag.*, Mar. 1996, pp. 114–21.

[23] F. Koperda and B. Lin, "First Phase Simulation for XDQRAP," IEEE 802.14-96/062, draft proposal.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