PCUP : Pipelined Cyclic Upstream Protocol over Hybrid Fiber Coax

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Abstract *In order to span NII (National Information Infrastructure) into the homes, the community cable TV networks have to be re-engineered to support two-way interactive services. In this work, we 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 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, which runs a contention-based tree walk algorithm, is executed periodically to allow the stations to join or leave. We also compare PCUP with various schemes proposed to IEEE 802.14 committee.*

1. Introduction

Cable companies have become the leading players in the search for ways to expand the ATM-based NII backbone network into the homes [1,4,5]. However, the community networks must support two-way asymmetric traffic patterns and arbitrate multiple accesses for available bandwidth. HFC [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 in upstream for HFC.

Fig. 1-1 represents a piece of a 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 miles in total length. Each branch serves 125 to 500 subscribers. One of the limitations here is that the station can not 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.

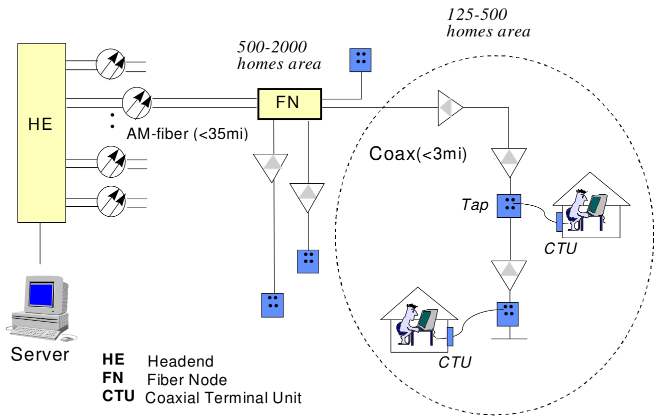

Figure 1-1 *The architecture of HFC. Subscribers in the feeder cable can only listen to the downstream from the headend and transmit in the allocated upstream.*

In practice, the analog band from a station to its headend is relatively narrow and of poor quality. In downstream, channel bandwidth is more abundant with less noise. A typical frequency spectrum for the subscribers to use is given in Fig. 1-2. Assume that a 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 broadcast programs, while digital downstream services such as 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 multiple upstream digital channels. These upstream channels are called "*multi-access channels*" and used to carry signaling and data. A larger bandwidth in downstream, 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 in upstream and 750 MHz to 800 MHz in downstream.

It is the upstream multi-access channel that this articles is addressing. The rest of the article is organized as follows. In section 2, we survey and compare the proposed

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MAC schemes. Our PCUP is presented in section 3 where protocol mechanisms and messages are defined. Section 4 evaluates PCUP and compares it with one distributed protocol, R-ALOHA, and, one centralized protocol, UniLINK. Finally, section 5 concludes the article.

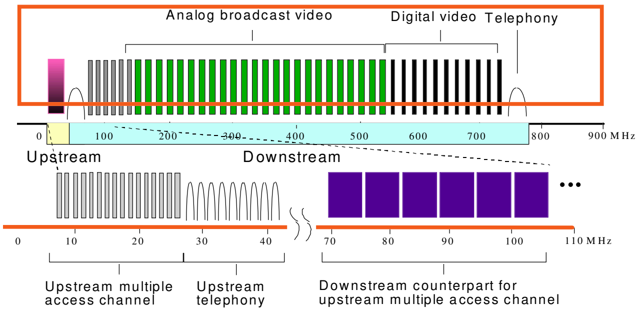

Figure 1-2 *Spectrum allocation of HFC.*

2. MAC Alternatives

The main goal of IEEE 802.14 Cable TV LAN MAC/PHY committee is to provide interactive multi-media 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 protocols and centralized protocols. There is no central controller in distributed protocols, like CSMA/CD and R-ALOHA[14] protocols. The centralized protocols provide better timing mechanisms in avoiding collisions. This kind of protocols, 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 Lab.[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), etc. We also present our CATV MAC protocol, PCUP, which will be detailed 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 to them besides that the station transmits its data immediately after the headend polls it.[19] In 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 FCFS fashion, informing the station by the 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. And the contention bandwidth is randomly accessed.[17,21]

In order to characterize these protocols, we make a comparison summarized in table 2-1. 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 2-1, we see that conventional MAC protocols can not meet the multi-media requirements. For example, the R-ALOHA protocol can not support isochronous due to its random access control. 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. Although ADAPt and UniLINK protocols are centralized and hybrid, contention-based bandwidth 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 ResolutTion (START-n) algorithm to ensure that a station can transmit in a chain of contention-free transmissions for a long message. In 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 a FPP frame, a station transmit its CBR, VBR and ABR traffic in three different regions, while in a PCUP frame, a station transmit these three consecutively. Furthermore, delay adjustment, which is also called positioning or ranging, is done by stations both in MLAP and FPP protocols. This adds up the station complexity. In CPR protocol, there are two factors that limits the 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, our PCUP stands out well in various aspects.

	R-ALOHA	MLAP	XDQRAP	ADAPt
Distributed	X			
Centralized		X	X	X
Isochronous bandwidth				X
Reservation bandwidth	X	X	X	X
Contention bandwidth	X		X	X
Scheduling discipline	none	fair scheduling	FCFS	FCFS
QoS		X	X	X
Timing implemented by	H/E	H/E & STU	H/E	H/E
Headend complexity	• •	• • • •	• • • •	• • • •
Station complexity	•	• •	• •	•

	UniLINK	CPR	FPP	PCUP
Distributed				
Centralized	X	X	X	X
Isochronous bandwidth	X			
Reservation bandwidth	X	X	X	X
Contention bandwidth	X			
Scheduling discipline	FCFS	FCFS	fair scheduling	fair scheduling
QoS	X	X	X	X
Timing implemented by	H/E & STU	H/E	H/E & STU	H/E
Headend complexity	• • • •	• • •	• • • •	• • •
Station complexity	• •	• •	• •	•

H/E = Headend STU = Set Top Unit (station)

Table 2-1 *Features comparison of proposed MAC protocols*

3. Pipelined Cyclic Upstream Protocol

3.1 System overall description

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 modes: cyclic transmission mode and negotiation mode as shown in Fig. 3-1. In Fig. 3-1, 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.

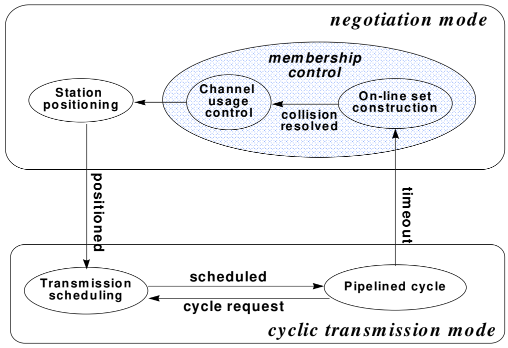

Figure 3-1 *State transition diagram of headend in the PCUP operations.*

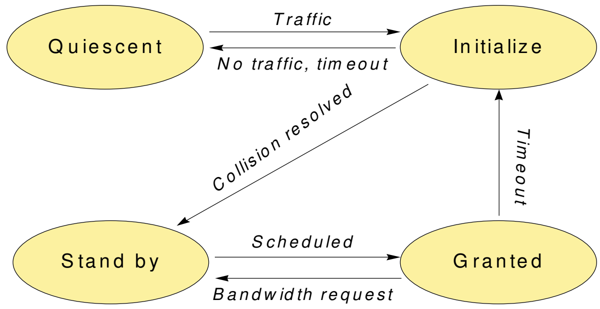

Figure 3-2 *State transition diagram of station in the PCUP operations. The initialize state includes station positioning and cycle membership control. Note that stand by is corresponding to transmission scheduling and granted is corresponding to pipelined cycle in the headend state transition diagram.*

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.

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 Fig. 3-2.

3.2 Membership control

3.2.1 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 0.3 second or more. The headend issues a *HE.invitation* frame 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 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 something, will be still on-line with no need to send them the *HE.invitation* frame.

3.2.2 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.

3.3 Station positioning

One uniqueness of HFC is that stations can not listen directly to the upstream transmissions from the 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 downstream and allocated upstream, respectively.

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 Fig. 3-3. In Fig. 3-3, *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

$$s_i+t_i+G = s_j+ \tau_{ij}, \qquad (3\text{-}1)$$

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 Fig. 3-4. It is obvious that the headend needs to position the stations correctly in order to schedule transmissions in this way.

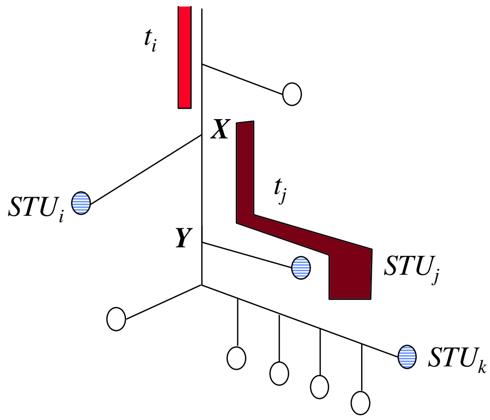

Figure 3-3 *The tree-and-branch topology with data transmission where STU_i has transmitted, and the STU_j is transmitting. STU_j is the predecessor of STU_k and the successor of STU_i.*

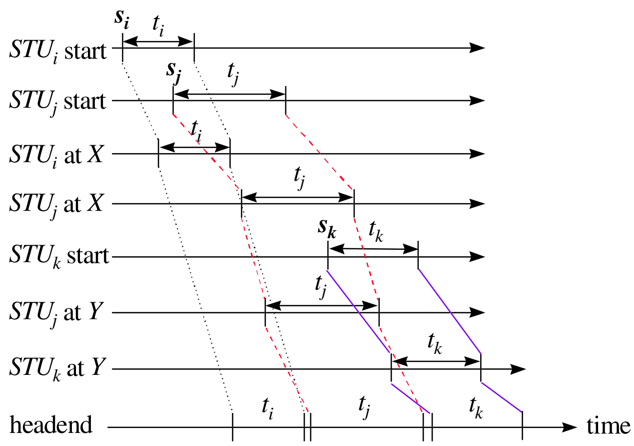

Figure 3-4 *The example timeline of pipelined data transmission. The convergence point of STU_i and STU_j is X; the convergence point of STU_j and STU_k is Y. We find that the successor starts its transmission before the end of its predecessor's transmission.*

The station positioning algorithm starts at headend. Headend sends a *HE.position* frame 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

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

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

$$\text{distance} = \lfloor (t_{rec} - t_{tx} - t_{overhead}) \div 2 \rfloor \times c \qquad (3\text{-}2)$$

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 specified by [10]. Headend sorts these stations in the increasing order of the distance.

3.4 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 3-1, 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 3-1 *Station slot requests, appended in the final slot of its transmission.*

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 described in equation 3-3. 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. βi 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, (i. (i, again, is used as the weight to distribute the capacity.

• EMBED Equation.2 • ´ • (3-3)

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

si = • EMBED Equation.2 • ´ •
(3-4)

Then, headend can assign a proper starting time and transmission duration time by the allocation frame, HE.schedule.

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 Fig. 3-5. 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 (s vs. 50 ms in some of our simulations, we need to look ahead only one cycle in most cases.

Figure 3-5 Look-ahead allocation.

3.5 Summary of PCUP

We now summarize the PCUP operations in Fig. 3-6 and Fig. 3-7. 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 3-6 *Pseudo code of station operations.*

IF (time up of *Group_Reset_Timer*)
cycle membership control
station positioning
ELSE
seize a cell from input buffer
process the cell, upgrade *Request_Table,* ack to station
issue *HE.schedule* frame if all the on-line stations requesting are collected

Figure 3-7 *Pseudo code of headend operations.*

4. 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 in section 4.1 and section 4.2., followed by the simulation results of R-ALOHA, UniLINK and PCUP .

4.1 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 Mbps to 10 Mbps 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 Mbps transmission rate per channel. By this assumption, 17, 14, 5 and 3 upstream channels can be used simultaneously. Since each branch serves 125 to 500 homes. That means each upstream channel is shared by about 30, 35, 100 and 167 subscribers respectively. The scale of network is assumed to be 80 km.
- 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.

4.2 Traffic models

Three types of traffic models, recommended by IEEE 802.14 cable TV protocols working group[24], are applied in the simulations. Traffic model A contains only ABR service. In traffic model B, the CBR applications contribute 50% traffic load, the rest 50% remains to be ABR. And in traffic model C, the VBR applications present 30% traffic, CBRs pump 30%, and the rest is for ABR service. Under these three traffic models, we examine the performance behavior of R_ALOHA, UniLINK and PCUP protocols.

4.3 Numerical results

4.3.1 System throughput

In Fig. 4-1 and Fig. 4-2, 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.

In Fig. 4-3, 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.

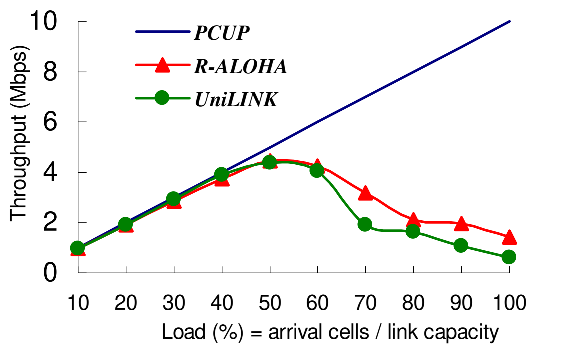

Figure 4-1 *Throughput of PCUP, R-ALOHA and UniLINK under traffic model A. The channel capacity is 10 Mbps.*

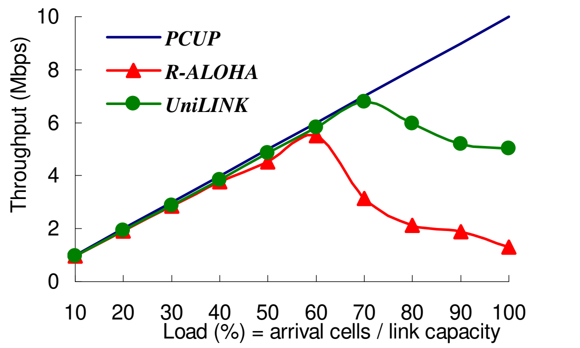

Figure 4-2 *Throughput of PCUP, R-ALOHA and UniLINK under traffic model B. The channel capacity is 10 Mbps.*

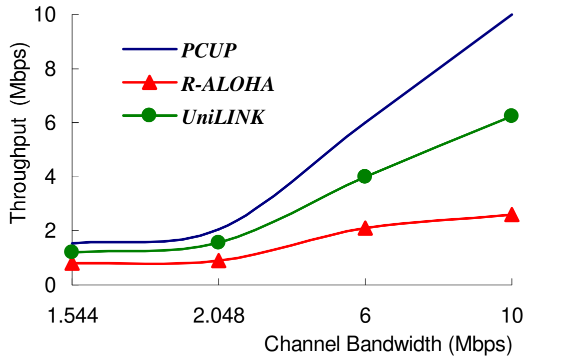

Figure 4-3 *Throughput of PCUP, R-ALOHA and UniLINK under different channel capacities. The traffic model is C and traffic load is 90%.*

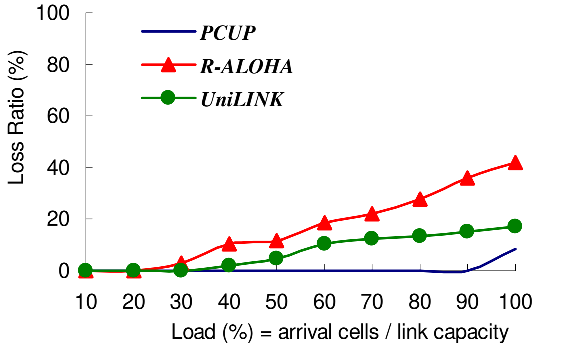

Figure 4-4 *ABR traffic lost ratio of PCUP, R-ALOHA and UniLINK under traffic model C.*

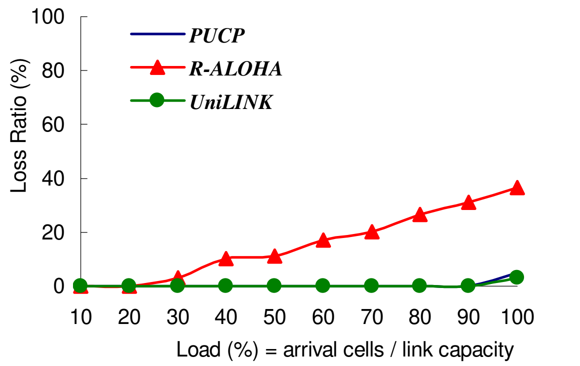

Figure 4-5 *CBR traffic lost ratio of PCUP, R-ALOHA and UniLINK under traffic model C.*

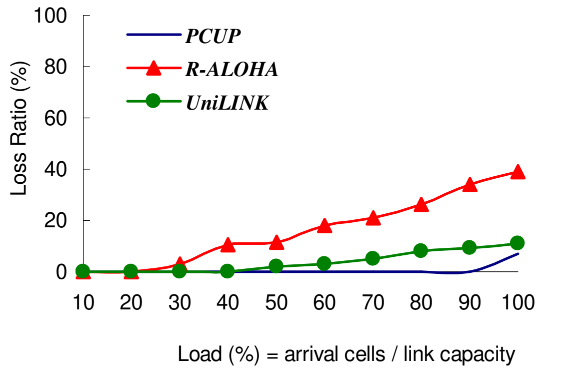

Figure 4-6 *VBR traffic lost ratio of PCUP, R-ALOHA and UniLINK under traffic model C.*

4.3.2 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. 4-4, 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. 4-5, 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. 4-6 with Fig. 4-4, the curves are similar, but UniLINK achieves lower loss ratio of VBR traffic. This scenario is due to applying reservation scheme over VBR traffic.

4.3.3 Access delay

In Fig. 4-7, 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. 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.

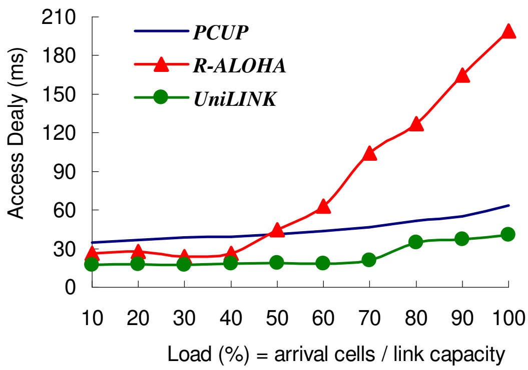

Figure 4-7 *Access delay of PCUP, R-ALOHA and UniLINK under traffic model A.*

4.3.4 Cell delay variance (CDV)

From Fig. 4-8 and Fig. 4-9, 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 VBR traffic since they are transmitted on the specified regions. PCUP is still remarkable in CDV performance under high throughput.

4.3.5 Fairness

Fairness is another issue while considering performance of an interactive CATV MAC protocol. In Fig. 4-10, 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.

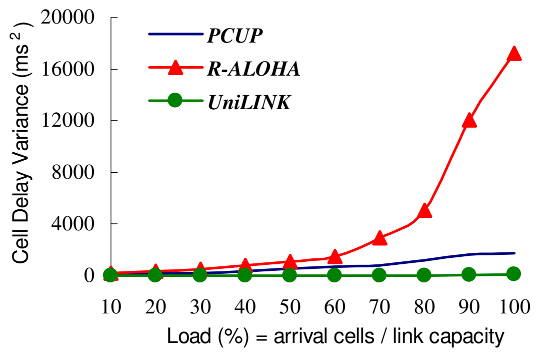

Figure 4-8 *CBR traffic cell delay variance(CDV) of PCUP, R-ALOHA and UniLINK under traffic model C.*

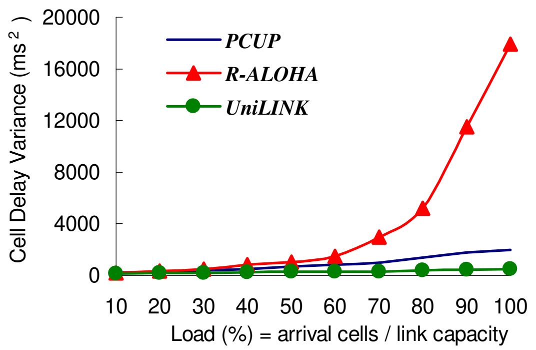

Figure 4-9 *VBR traffic cell delay variance(CDV) of PCUP, R-ALOHA and UniLINK under traffic model C.*

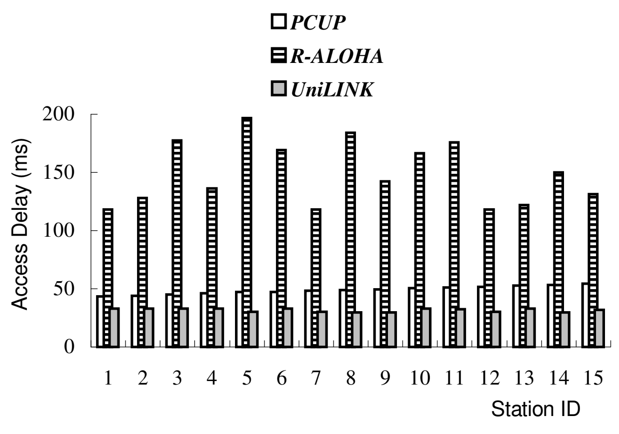

Figure 4-10 *Access delay of PCUP, R-ALOHA and UniLINK under traffic model C. The channel bandwidth is 10 Mbps and traffic load is 90%.*

5. Conclusions

To achieve interactive broadband multimedia services 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 for various traffic types. We have proposed a centralized and hybrid MAC protocol, PCUP, for IEEE 802.14 network. It provides integrated broadband services to the home and supports QoS for various types of traffic. PCUP's performance is contributed by several features: 1) a membership control which periodically updates the set of on-line stations and the channel usage status, 2) a synchronization process which neutralizes stations' propagation offsets, and 3) 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%. When the load is below 95%, the throughput for PCUP is close to the theoretical bounds and no loss occurs. Concerning the random access protocols under medium to heavy load, re-transmitted 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.

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