Using a multiple priority reservation MAC to support differentiated services over HFC systems

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SUMMARY
The successful commercial deployment of Hybrid Fibre/Coaxial (HFC) access networks in the residential market has so far been driven by demand for faster Internet access and the prospects of a host of new services based on real-time voice and video. To sustain their growth rates and compete with alternative approaches, such as ADSL, they must be enhanced with the capability to efficiently handle quality-intensive real-time services. The new multi-service paradigm mandates isolation of traffic classes, conditioning of entering traffic and preventive control in addition to traditional closed-loop control. The differentiated services (DiffServ) architecture with its relevant traffic control tools and the bundling of behaviour aggregates is particularly suited to the H/W-based MAC of HFC systems. It constitutes a suitable framework enabling the support of proliferating real-time voice- and video-based services while aligning the system to the emerging Internet strategy of scalable service differentiation. The implementation of such a solution in the ACTS 327AROMA research project is presented in this paper. The performance of the system is evaluated using computer simulation. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: HFC; MAC protocols; differentiated services; tree topology; access networks; cable modems; residential services; QoS

1. INTRODUCTION

Tree-shaped topologies, a natural choice for distributive services, still offer attractive cost advantages for bi-directional broadband access networks by allowing many customers to share the expensive head-end equipment and the feeder section. Retrofitted with fibre feeders and enhanced with a return channel they possess the significant advantage as broadband access platforms of exploiting the legacy copper last drops to the homes, at least during the crucial introductory phase and probably for many years to come. Re-use of the existing infrastructure greatly reduces the initial investment outlay and provides a graceful upgrade path in step with...
service demand. Typical examples are Hybrid Fibre Coaxial (HFC) and Passive Optical Network (PON) systems. The first exploit legacy Community Antenna TV (CATV) systems and their coaxial medium beyond the fibre node, while the latter can re-use the twisted pair-based telephone networks beyond the Optical Network Unit (OUN). In both systems, sharing of the upstream (from customer to network) channel is usually effected through TDMA multiplexing. A Medium Access Control (MAC) protocol is employed to arbitrate the access to the slotted common medium by allocating slots to customer terminations according to demand [1–6].

The currently deployed HFC systems are mainly used for fast Internet access since, in principle, they outperform V.90 modems and ISDN lines. However, because of the TDMA sharing of upstream bandwidth, the customer enjoys a satisfactory throughput only while the number of simultaneously active terminals is relatively low. With a typical rate of 30–40 Mbps in the downstream and 2–3 Mbps upstream, the average throughput becomes the same as with telephone line modems for about 600–700 customers in the downstream and just around 50 in the upstream! Complaints of slow performance have already surfaced. This is a weak point in every shared-medium-based network, tolerated for its lower cost. Thus, common sense dictated to start with clusters of several thousand homes passed as was the practice in the legacy CATV systems (10 000–20 000 homes). This provided cost-effectiveness while the initially very low average intensities of the new users did not overload the network. However, as penetration of subscribers and their usage levels rise, the number of customers per cluster must be reduced, by introducing more fibre nodes, thus creating a larger number of smaller clusters. It is clear that if new bandwidth-hungry, video-based, delay-sensitive services (e.g. tele-conferencing, tele-education, home security monitoring, interactive games, voice over cable, etc.) start spreading, then the cluster size will have to come down to a couple of 100 subscribers and quality support will become imperative to compete with xDSL.

From a traffic engineering point of view, the tree-shaped access system exhibits a very different behaviour between the upstream (from customers to core) and the downstream direction (from core to the customers). In the downstream, the broadcast nature of the medium creates replicas of the signal (in the passive splitters of PONs or the taps of HFC systems) and encryption is used to restore privacy and security. The upstream works as a distributed queuing system characterized by the long time required to pass control information from the queuing points to the service controller residing at the head-end in the root of the tree topology. As shown in Figure 1, transmissions from the cable modems are emitted at slot limits so as to converge without collisions or wasted gaps (except for a small guard-band).

The allocation of upstream slots in a tree-topology access system is based on a pipelined reservation method, which allows to dynamically adapt the bandwidth distribution to traffic fluctuations [1–3, 6]. The MAC controller uses these globally collected access requests to allocate the upstream slots by sending a number of access permits to each modem matching the waiting traffic. Thus, the service policy of the distributed multiplexing function is governed by the MAC algorithm and the delay performance is dominated by the considerable delay for the acquisition of arrival information, a new element not found in the centralized multiplexing taking place in a typical switch queuing point. In contrast, drop policies (regulating how packets are dropped from almost full buffers e.g. ‘early packet discard’) must be distributed over all network terminations (cable modems) where the flow identity and fill levels are known.

Because of the large reservation delay and statistical behaviour of the aggregations from many customers, special care must be taken to safeguard quality of service (QoS) from sensitive traffic. Any indiscriminate mixing with best-effort traffic results in unacceptable damage to the
QoS-sensitive service. The closed-loop congestion control of TCP is triggered by the detection of losses, i.e., the source rate rises until the bottlenecked buffer is filled to overflow. Loss is an inherent functional feature of TCP flow/congestion control strategy enabling it to adapt to unknown intermediate network conditions. Losses in TCP flows are easily corrected by retransmissions. However, whenever these overflowing buffers are shared by QoS-sensitive traffic, the resulting indiscriminate losses will also affect flows that cannot afford retransmissions damaging irreversibly the real-time services. Since the TCP approach of closed-loop control is not applicable to delay sensitive traffic, service isolation and resource guarantees are indispensable. Further differentiation is necessary among services with strict delay requirements and just better-than-best-effort traffic. This will enable tariff differentiation for TCP-based services, which in fact do carry traffic critical to the operations of a user (e.g., in the case of a home office or an SME relying on e-commerce) requiring a minimum guaranteed throughput even if strict delay requirements are not imperative. The above reasons make expedient a prioritization scheme and the differentiated services strategy of IETF [7] is a very suitable approach to handle the problem. The number of traffic classes, however, is limited by the scarcity and cost of MAC control resources, not allowing a fine resolution in the choice of the unit of bandwidth allocation. Thus a coarser classification into just a few traffic aggregates is inevitable, but is still in the spirit of the philosophy of DiffServ.

In the HFC system implemented and field-trialled in the framework of the European ACTS AC327 ‘AROMA’ project, a mix of native ATM, IP-based quality services, better-than-best-effort and plain best-effort services were concurrently supported. The main tool was a DiffServ-aligned MAC protocol with a suitable mix of bandwidth allocation mechanisms. This protocol relies on the following three innovative features: a DiffServ-aligned prioritization architecture, simultaneous collection of multiple requests from all class queues, and a slot-by-slot channel agility over three upstream channels. The way these features create a QoS-enabled MAC is discussed in Section 2. The concept of operation of the MAC protocol is presented in Section 3.
while the actual implementation in Section 4. Its performance is evaluated in Section 5 using computer simulation and conclusions are reached in the next section.

2. SERVICE DIFFERENTIATION IN TREE-TOPOLOGY ACCESS NETWORKS

The current generation of cable modems employs a MAC based on reservation Aloha. This access method employs special contention slots [2], or (for efficiency) mini-slots [1, 3], where modems place reservations (requests for a number of upstream slots). These mini-slots are available on a contention basis (i.e. Aloha) and they are used to set the reservation process going. Because as is well-known, contention has low efficiency due to collisions, it is not used for the payload slots which are assigned deterministically at a second stage on the basis of the number of slots already requested. A successful contention is followed by a chain of further reservations using another request field piggy-backed in each upstream slot, where each modem announces the new traffic that arrived while the previous cell was waiting for its own access permit. The contention slots or mini-slots solve the problem of letting the MAC controller in the head-end know the arrival of the first cell of a new burst which can never be announced by piggy-back requests, if it arrives in an empty queue.

The use of contention is far more efficient than round-robin polling when the number of modems is high with each one providing a small and bursty traffic load. The overhead of round-robin polling increases in proportion to the number of modems, and it becomes prohibitive above a couple of 100 modems (even when mini-slots are used). So contention is used in the currently deployed HFC systems to offer mainly Internet access with several hundred or even a few thousand modems sharing each FDM channel. However, as explained in the introduction, such cluster sizes will have to come down for broadband real-time traffic and polling particularly using mini-slots [4,6] can become a viable alternative for up to a couple of 100 modems.

The use of contention when different classes must be differentiated, creates a host of new complexities which can only be justified if the number of modems in the cluster is kept to sizes precluding polling as happens today. The biggest implication is that the contention process must also be differentiated, i.e. the head-end must announce the class of each contention slot so that only modems having traffic of the relevant quality class will contend [8]. The contention resolution must also be differentiated accordingly. However, this solution is complex and, more important, presents great variation of the worst case of access delay due to the statistical nature of collisions and collision resolution. This is a serious drawback for services sensitive to delay variation. In contrast, polling has a fixed worst-case request acquisition time making it preferable for a demanding QoS environment, particularly in combination with mini-slots. Furthermore, it allows each request, whether in the polling mini-slot or piggy-back field, to provide simultaneously the information for all queues.

The request field in the AROMA system provides three sub-fields for announcing separately the arrivals in each of the three reservation-based queues. The multiple requests are the tool for the higher QoS capabilities of this system. They are necessary if higher priority traffic is to be quickly made known to the head-end. This feature enables the algorithm in the MAC to offer precedence to the high priority cells when issuing access permits on a global basis and not just among the cells of the same termination, which is of a very limited value. The payload of each slot can accommodate one ATM cell, so the target of each permit is one cell, which is the
quantum of bandwidth allocation in the system. No class is identified in the permit (only requests specify class) leaving the cable modem to use it for the highest priority cell in all queues following the logic shown in Figure 2, where the priority queue system of the modem is depicted.

ATM slotting is the solution adopted by many standards bodies, like DAVIC 1.3 and 1.4, DVB/ETSI ETS 300 800 [2], (now incorporated in DAVIC), and IEEE 802.14 [3] but in DOCSIS [1] it was only a future option. For IP packets, several slots, enough to accommodate the IP frame, are successively assigned. Fixed short slotting facilitated the H/W implementation of the MAC and is used to advantage in the context of the DiffServ architecture over a slow, shared link such as HFC. In this context, it allows the suspension of the transmission of a lower priority packet on the boundary of a slot (cell), and the transmission of delay-sensitive packets before resuming the transmission of the low priority one. This is done automatically by MAC H/W without any knowledge of packet delineation.

Traffic asymmetry between the upstream and downstream is expected to decrease and this creates the necessity to increase the upstream bandwidth available to customers, particularly professionals with home offices. Since noise funneling and other impairments do not allow a wider than 2 MHz upstream channel, the described system resorted to an upstream transceiver (developed by Alcatel SEL) capable of sharing more than one upstream channel. Three channels were chosen for cost-efficiency reasons in the implementation of the burst mode transmitter. Although frequency agility is common in HFC modems, it operates presently under management procedures over time scales of seconds, whereas in this case it operates under MAC control on a slot-by-slot basis allowing more effective upstream bandwidth per cluster by improved statistical gain among the three upstream channels.

The DiffServ strategy recently adopted by IETF as a scalable and relatively simple methodology towards enriching with QoS the IP services, is applicable and quite appropriate in the case of such tree-shaped access systems. To align such an access system to the differentiated
services concept, new provisions must be incorporated in the MAC function since the MAC
governs the multiplexing policy. Thus each flow aggregation as defined by the DiffServ
specification must receive the per-hop-behaviour (PHB) which respects its specific requirements.
It is not possible to offer such functionality as a software upgrade because the MAC requires at
least in part a fast H/W implementation. Each QoS class must encounter the specified per-hop-
behaviour (PHB) across the multiplexing points against the competing flows or at least not be
delayed in a way that cannot be recovered in the next fully DiffServ–compliant node. Even
before the emergence of the DiffServ architecture, it had become apparent that differentiation in
the handling of traffic classes was required in the MAC function of PONs and HFC systems [5].
This was reflected in the adopted MAC solutions in the EU research projects PLANET [9] and
ATHOC [6]. These demonstrator systems supported both delay-sensitive and best-effort
services.

The expedience that led to the DiffServ architecture by IETF was the emergence of
requirements for ISPs to offer QoS to certain flows in the presence of disturbing plain best-effort
traffic without complex maintenance of state information in core routers. Eventually quality
cannot be guaranteed without some maintenance of state variables relating to reservations and
flow intensities but the strength of DiffServ lies in the slow and graceful introduction of such
complexities in line with revenues from a previous stage of introduction of such mechanisms.
Dealing with behaviour aggregates and starting with static management-based Service Level
Agreements (SLAs) executed at slow time scales while keeping traffic conditioning at the edges
of the network enables a low-cost starting phase while smaller granularity levels can be sought
out at later stages of deployment. Non-compliant intermediate nodes can be transparent but at
the risk of reduced overall performance should they become the bottleneck in the route of flow.
Slow distributed access multiplexers (such as an HFC system) residing at the network edge
cannot be relied upon to operate in a transparent fashion as regards the DiffServ strategy since
the MAC directly affects the temporal properties of the egress stream. So the DiffServ
architecture is a befitting choice for tree-shaped access networks as much as it is for any other
network supporting quality-demanding traffic.

Given the fluidity of the standardization of QoS traffic and the several options open for PHB
variations [7, 10], a flexible strategy is needed that can accommodate the changing environment.
In the sections below, a MAC design approach is presented which can execute the currently
available PHBs and adapt to a broader framework of service differentiation in the event of new
emerging services. The basis of the approach is the use of access priorities in the reservation
system, which can be programmed to fit with required PHBs by means of the mapping of flows
to priorities. Local schedulers at the modem are of little value but drop policies as required for
the AF classes [11] can usefully be applied independently to each modem queuing points.
Logically separate queues for each priority are necessary for the proper operation of the
prioritization scheme.

3. DESIGN OF A DIFFERENTIATED SERVICES MAC FUNCTION

As in the centralized multiplexer case, flows with demanding QoS (e.g. expedited forwarding or
assured forwarding) must be identified and receive properly differentiated treatment from the
plain best-effort traffic. This is accomplished in the cable modem by placing the corresponding
cells in the high-priority queues which will subsequently place higher-priority requests and activate the higher-priority permit allocation MAC algorithms.

To reduce complexity in this cost-sensitive residential access system, services are grouped into behaviour aggregates (classes) with a similar set of requirements. This is in line with the DiffServ philosophy of flow aggregation for better scalability and flexibility. Hence, four priority classes were implemented in the MAC, leaving finer aggregations and more elaborate forwarding policies, to be implemented in the router at the egress of the HFC system. All that is required from the MAC is not to deny quality to any groups of flows. Finer resolution in such a distributed queuing and scheduling system would have meant exchange of prohibitively large amounts of control information utilizing useful bandwidth.

The characteristics of the four aggregation levels (priorities) chosen are the following:

- The highest priority is devoted to delay-sensitive periodic CBR traffic which is supported by pre-allocated pre-arbitrated, unsolicited permits issued on a periodic basis by the MAC controller. This class is suitable for services with very strict delay requirements, which undergo strict traffic profile control (traffic conditioning) such as the expedited forwarding (EF) service [10].

- The second priority level is devoted to real-time variable rate flows, typical of compressed video or VoIP and it is provided with peak rate policing for guaranteed QoS. MAC exercises a policing function by rate checking before issuing the permits. This check is based on credit allocation at the time of subscription or connection set-up. In the DiffServ context, it could be used for the top assured forwarding (AF) class.

- The third priority is devoted to data services with higher requirements than best-effort, typically a minimum guaranteed throughput. The traffic profile control assumed for this class aims at minimizing the loss of packets and the disturbance to other traffic. The credit scheme is used to guarantee a minimum rate (serve while credits last) while traffic exceeding this limit is relegated to the fourth priority permit generation. The third priority mechanism is suited to support all four or the lower three AF classes [11]. (Drop policies can be independently applied at the modem queuing points).

- The fourth priority is reserved for plain best-effort services which employ loss-based flow control at the TCP level and can be very disruptive to the other classes when sharing the same queue.

Note that the last three priorities employ reservation while the first fixed, pre-arbitrated permits. The reservations operate by means of three request fields using two bits for the second class and three bits for the other two (occupying a byte in total as shown at the right-hand bottom corner of Figure 3) which is embedded in every upstream slot. In the AROMA system, this byte uses the place of the header error control (HEC) field of the ATM cell which is not needed for cell delineation since an additional synchronization preamble is employed because of the burst mode operation. The total length of the upstream slot has in the AROMA system a size of 64 bytes accommodating apart from the one-cell payload a synchronization preamble. The speed of the upstream is 3 Mbps but the slot-by-slot agility over a triple of FDM channels allows further dynamic statistical load balancing over all the customers of three channels, i.e. the MAC controller assigns not just a slot but also a channel. The frame structure in the downstream direction is dictated by several mandates of the physical layer (synchronization, flexibility over many modulation constellations and rates adapting to plant conditions,
interleaving, Reed–Solomon FEC, etc). These issues are covered in the relevant standards, e.g. References [1–3], and will not be discussed here since we focus on the traffic multiplexing issues. The physical layer in AROMA follows the DVB standard [2]. For the operation of the MAC, all that is important is that a number of permits is provided in a periodic basis corresponding to the number of upstream slots over the same period.

4. IMPLEMENTATION OF THE PERMIT GENERATION PROCESS

The block diagram of the MAC H/W is shown in Figure 4. The permit allocation algorithm will be described with the help of Figure 3, which illustrates the concept of operation.

The top priority employs a list of 512 permits, which has been prepared by the embedded processor on the basis of subscription data. The list is cyclically read out by the MAC controller H/W, and the permits are sent embedded in the downstream frame. Since ATM signalling is also supported in AROMA, the list can be updated dynamically to add new connections using a second copy. At the end of the read cycle, the H/W is switched over to the updated copy. Techniques to space the permits in the list are given in Reference [9].

The other three priorities are serviced dynamically on the basis of the collected requests by filling in the locations that are left empty in the list (representing unallocated bandwidth). The requests per queue/priority arriving at the MAC controller in the head-end contain the number of new arrivals (in ATM cells). The MAC H/W adds the new values to the three outstanding request totals for each modem and queue, thus creating a reflection of the corresponding buffer...
fill levels, albeit with a delay equal to the time for the propagation of the information. At the same time, the downstream permit positions in the frame are filled with permits produced by the permit generator engine, which is continuously scanning in a round-robin fashion the outstanding request counters, reducing them by one for each permit scheduled. The higher priority counters are inspected first and only if all are empty the same process is repeated for the immediately lower priority. To expedite the process, flags are used to quickly detect and skip all empty locations.

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So, the whole MAC implementation uses a combination of firmware and H/W. The permit-list is handled by the embedded processor and the H/W executes a sequential read passing the permits to the exit until it detects a null. This triggers the search engine, which seeks to find the next modem to service in the round-robin line inspecting the outstanding request counters. This action is intended to serve cells queued in the distributed modem queues respecting the global absolute priority among the three levels. The overall policy is a round-robin service among the different modems with absolute priority as regards the different service class queues of all modems.

The permit generation is subject to some additional checks and guarantees by force of a companion credit check process. At the end of each cycle, the embedded controller updates a list of credits corresponding to the established peak rate of connections for the second priority (credit fetch logic). The MAC H/W subtracts the credits as it issues permits and stops serving any modem queue that exceeded its second class allocated apportionment. This policing action guarantees that malicious users cannot disturb complying traffic but only their own lower priority traffic. The credit check is used differently in the third priority. When credits are exhausted, leftover requests are added to the fourth priority ones; thus a minimum rate is guaranteed but any excess is considered plain best-effort, in accordance with AF rules.

5. PERFORMANCE EVALUATION OF THE MAC

The behaviour of the above MAC mechanisms was studied with the help of a computer simulation model created with the PTOLEMY tool. The scenarios used 10 cable modems loaded with uniform traffic for each priority. The slot (170.6 \( \mu \)s) was used as a time unit. The traffic sources used the common ON–OFF model generating traffic at the slot/cell level with exponentially distributed on and off periods. The peak rate was the system rate simulating the arrival of IP packets with geometrically distributed lengths, which were instantaneously segmented into slots. No credits were simulated since they would only be meaningful with malicious sources and then the effect is easily predictable and does not warrant the use of simulation. The runs used a total cell generation of half a million cells since the heavy PTOLEMY model over the Solaris OS used was relatively slow precluding longer runs.

The first priority will not be presented since it exhibits deterministic behaviour with the delay never exceeding the fixed permit distance as pre-programmed in the list. (More on the behaviour of such an approach is given in Reference [9]).

Figure 5 depicts the probability distribution function (pdf) of the access delay for the three priorities under a total load of 85%. Only the variable part of the delay is shown, i.e. the fixed round trip time of about four slots for the travel of the request upstream and the permit downstream, is not included. (Note that the round trip delay has been equalized for all the branches of the tree by introducing a suitable electronic delay calculated by means of a ranging process which takes place at modem initialization.) The first priority CBR traffic which is based on the pre-programmed permits was using 10% of the load with the other 75% equally distributed among the other three priorities. The delay advantage provided by the prioritization leads to almost all the slots of the second priority accessing in less than 250 slots (i.e. 43 ms) while those of the third in less than 350 slots (60 ms). Of course, there is no bound for the fourth priority which can exceed any limit depending on the total loading.
The pdf of delay under a higher offered load of 110% is shown in Figure 6. Again 10% of load was rigidly allocated to permits in the first priority list. The second priority sources offered a load equal to 30% of capacity, while the third offered another 30% with the fourth contributing 40%. The first two priorities do not exhibit any significant behaviour difference with the previous scenario, since they encounter a lightly loaded medium as before. The effect of prioritization is exactly to hide the presence of any lower priority traffic, which is prevented from competing against the protected sensitive traffic. The effect on the fourth priority is very strong since it is throttled down to the 30% of capacity left over from the other three. Its average delay is not bounded. However, in Figure 6, only the cells that managed to get through are included showing a low probability to depart at any delay value as they seek ‘holes’ left out in the permit generation of the higher priority traffic. The line extends, of course, theoretically up to infinity but only a small section of the very large values that occurred in the simulation run is included in the figure. This is better illustrated in Figure 7 which shows buffer fill levels for each priority. The tendency to an almost linear long-term increase of the fourth buffer is clear due to the steady long-term average cell-generation rate by the ON–OFF source model.

However, it is worth noting that the sources used in this run do not model higher layers where the typical congestion avoidance of TCP would exercise flow control in response to losses and reduce the rate, while retransmitting lost packets. So the system, thanks to prioritization, can guarantee the performance enjoyed by sensitive traffic while exploiting any unreserved bandwidth for the support of best-effort traffic. Therefore, the overall result is a quite efficient system. The high-priority traffic represents high-revenue services demanding satisfactory performance while the accommodation of fourth priority best-effort traffic guarantees a high
Figure 6. Pdf of access delay.

Figure 7. Buffer size evolution with time.
system utilization. This is achieved with no harm to the TCP-based services, since in real-life instead of a tendency to infinite buffer overflows and unbounded delays, the rates of the sources would adapt to the possible bottleneck sharing the spare capacity equally among them.

It is useful to outline at this point how the MAC service policies can be mapped to actual customer services. The system provides enough flexibility to accommodate a large variety of policies in conjunction, of course, with tariff scheme. The previous results show that the difference in performance between the second and the third priority strongly depends on the network operator’s bandwidth allocation policy. Very demanding applications can use the first priority but if the bit rate of the traffic is variable, the results show that it is also possible to guarantee quite strict delay and jitter performance using the second priority and this is much more cost-effective. The performance of the third priority is not suitable in general for real-time traffic unless very conservative peak rate allocation is employed for the second priority. This is not however the intention since it would not be an efficient solution and thus the third priority is usefully intended for better-than-best-effort traffic which does not enjoy guaranteed delay (disturbed by second priority traffic fluctuations) but a guaranteed minimum long-term throughput. Thus it is suitable for a higher priced Internet access service for professionals, leaving the fourth priority as a poor man’s Internet access certainly coupled with a low tariff. A connection acceptance policy to guarantee resource availability for the QoS-demanding services, such as simple over-provisioning or fully dynamic SLAs (e.g. using RSVP) is of course assumed. Any such scheme should probably allow for some spare bandwidth to protect plain best-effort service users from the frustration of bandwidth starvation at times of overload.

These considerations show an efficient overall exploitation strategy of the system based on the fortunate synergy between the behaviour of demanding and best-effort traffic. The latter, thanks to its closed-loop congestion control, can provide the necessary leeway for the statistical gain of the preventive control-based services. In other words, if we did not have the lower class we would have either to accept less high-quality traffic or leave the excess bandwidth unutilized in an effort to avoid performance degradation during statistical extremes. It is the availability of closed-loop congestion control of TCP that allows us to offer both guaranteed performance to demanding traffic and good system resource utilization, at the same time.

To close the performance assessment, the mean delay as a function of the total load is depicted in Figure 8 for each priority. As in all cases, 10% was provided by the list as necessary for the polling of new bursts and the rest equally distributed among the priorities and modems in a way that the total was the one shown on the horizontal axis. For comparison, a simulation run with the same load but indiscriminately mixing all sources in one queue without prioritization, is included as the line marked “all”. The delay for the first priorities increases very smoothly with the load leaving the fourth priority to suffer the congestion with the delay increasing asymptotically to the 100% line as is typical of any queuing system. The buffer size increases of course without limit.

Comparing the upward knee of the “all” and third priority curves (which marks the load region where delay becomes unacceptable for the sensitive part of the traffic), we observe that priorities allow quality guarantees to be effective up to the full system load. This of course will be true in real life only in conjunction with a preventive connection acceptance agreement. Also note that the knee of the second priority will never be reached in real systems as it does not occur except well above 100% total offered load in the simulations. Figure 8 shows, of course, the average delay performance but also important for real-time services is the variation of delay, which as deduced from Figures 5 and 6 is quite restricted for the high priorities. Variation is not
as important for the third and fourth priority classes where it is mainly the throughput that matters.

The measurements from the lab demo confirm the simulation results even though only two modems were available for the lab experiments.

6. CONCLUSIONS

Tree-shaped shared medium access networks such as PONs and HFC effect a distributed multiplexing function which concentrates traffic from many users and many services with diverse requirements. To be able to guarantee that the QoS of sensitive traffic will not be disturbed by best-effort data traffic requires embedding differentiated support for flow aggregates with common requirements. The DiffServ architecture is quite advantageous in this context and the multiplexing function has to be aligned to it. The execution of PHBs cannot be effected without the co-operation of the MAC protocol, which is in charge of the bandwidth distribution to the competing cable modems. Special provisions have to be embedded in the MAC design based on differentiated handling of flow aggregates. The drop policies on the other hand are no different than in any queuing point since, contrary to the delay policy situation, the required information is not distributed but locally available. The evaluation of the application of this methodology in the AROMA HFC multi-QoS system shows that this approach aligns the system to the mandates of the DiffServ architecture and satisfies the diverse requirements of
several service classes simultaneously. This is achieved by a synergy of several MAC service mechanisms exploiting the consistency of preventively controlled traffic while taking advantage of the traffic profile tolerances afforded by closed loop control. Finally, it is worth noting that the described MAC solution can be easily adapted to a PON system where polling is the only feasible reservation strategy.

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