Efficient Transport of Packets with QoS in an FSAN-Aligned GPON

John D. Angelopoulos, Helen-C. Leligou, Theodore Argyriou, and Stelios Zontos, National Technical University of Athens

Edwin Ringoot and Tom Van Caenegem, Alcatel Research and Innovation, Antwerpen

ABSTRACT

The standardization of passive optical networks capable of transporting Ethernet frames at gigabit-per-second speeds, currently in progress in both ITU-T and IEEE, constitutes a major milestone toward cost-effective photonization of the last (aka first) mile. This article presents an Ethernet Gigabit PON (GPON) system aligned with the philosophy of the evolving FSAN/ITU-T specification, which focuses on the efficient support of any level of quality of service. The intelligence of this system, in terms of traffic quality guarantees, lies in the MAC protocol, which controls the distributed multiplexing/concentration function by allocating variable length slots to every user of the shared upstream (toward the network) medium. The way transport of information is organized in an ITU-T GPON system and the operation of a MAC protocol that preserves all QoS guarantees are presented and evaluated in this article.

INTRODUCTION

Not unlike the flow of water in nature, the metaphorical trickle of traffic from hundreds of millions of residential links flows into multi-megabit-per-second metropolitan links, which in turn are the tributaries that create multigigabit-per-second core links. A similar course follows the traffic from corporate or smaller businesses, where again the larger aggregates are collected from many small initial streams of business terminals. There is, however, a significant difference in the way concentration takes place for these two kinds of traffic, which explains the inertia in extending fiber into the residential local loop (the defiant last bastion of copper in public networks). The underlying cause lies in the topologically different structure of the domains of ownership, which impedes early concentration in the residential access. In the business case, many terminals of same ownership are in close proximity, which allows for very cost-effective aggregation of traffic by means of short and mostly shared links created with very low-cost LAN technology, mostly Ethernet-based. In the residential case, the traffic has to travel a significant distance to the Internet service provider (ISP) point of presence (PoP) before concentration can allow transport methods with lower cost (per megabit per second) to be applied. Thus, fragmented ownership becomes the factor inhibiting cost-effective use of fiber in the loop (FITL), since photonics only become viable at higher traffic rates.

In the quest for a way to lower the economic break-even point by sharing expensive optical links in the residential market, passive optical networks (PONs) emerged in the late ’80s from BT Labs as the answer to the problem. However, inadequate demand due to lack of enticing applications to stimulate it resulted in rather poor results as exemplified by the ill-fated Optical Access Line (OPAL) program of Deutsche Telekom in Germany, which started with pilot installations in 1991–1992. But instead of accelerating, the program was later abandoned despite the award of contracts for commercial deployment to 220,000 households [1]. Still, asynchronous transfer mode (ATM)-based PONs (APONs) were standardized by the Full Services Access Network (FSAN) consortium and adopted by the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) in 1998 as G983.1 [2]. However, the deployment of this broadband PON (B-PON) technology has not yet reached significant levels. Despite the potential for generating high revenues when deploying a B-PON offering triple-play services, many operators are still reluctant because of the relatively high investment costs involved.

Although for the time being the projected penetration of optical fiber into the local loop fell far short of expectations, the effort to develop cost-effective fiber access systems continues unabated as witnessed by the ongoing standardization work in the Ethernet in the First Mile (EFM) initiative of the IEEE and the GPON of FSAN/ITU-T [3]. The rationale behind the perseverance of the idea of FITL lies in the fact that although the time for the massive introduction of fiber is quite uncertain, the eventual displacement of copper by fiber in access, as happened in the rest of the transmission plant, is indisputable.

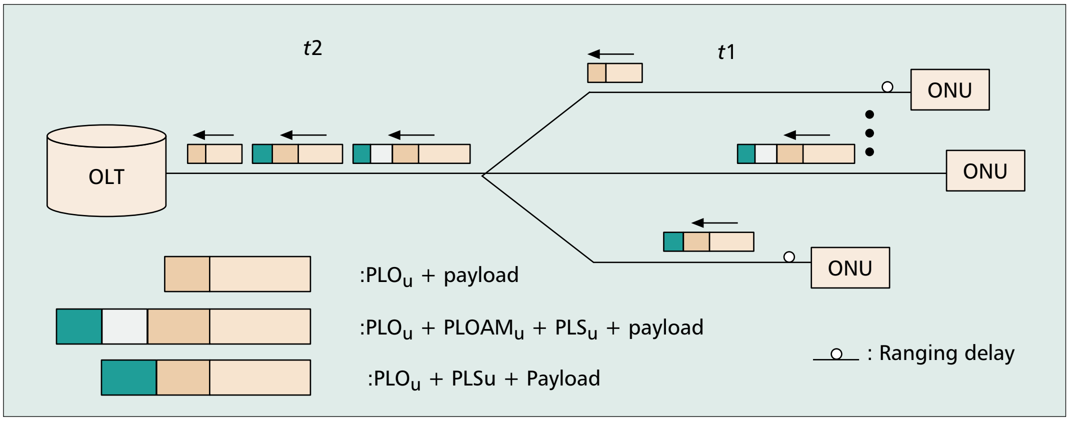

Figure 1. *The concept of TDMA operation upstream.*

The studies of the GIANT project have heavily influenced Alcatel's contributions to the FSAN initiative, but are also in turn aligned to FSAN standardization decisions as they become available.

The trend is irreversible as the costs of optics are coming down, bandwidth demand is going up, and optical networking spreads in the metropolitan areas, all working to drift the cost-related break-even point closer to the realm of optical superiority. The major drive behind the Ethernet GPON and EPON standardization efforts is the fact that the prevalence of packetized data traffic has increased dramatically over the last decade, due basically to the Ethernet-in-the-LAN success story and the fact that the majority of services are now transported over IP.

The traditional star topology of residential access does not allow true aggregation per neighborhood before reaching the user-network boundary, since the traffic needs to be commissioned (including service level agreement, SLA, establishment), checked for compliance (policed), charged, and monitored per customer, leading to the unavoidable cost burden of any retail sale situation. Thus, the user–network interfaces must stay near the customer. PON technology relieves this problem, allowing the traffic from different customers to be multiplexed using time-division multiple access (TDMA) under the arbitration of the medium access control (MAC) protocol in the upstream direction. So while the interfaces remain in the optical network unit (ONU) at the customer curb, building, or even home, the control is exercised by the optical line termination (OLT) at the root of the tree residing in the protected environment of the operator's central office. From there, the MAC protocol controls and polices the rates per customer, achieving significant cost reduction due to aggregation into a shared medium apart from that resulting from less fiber and the sharing of one optical transceiver for all customers on the network side (in the OLT). Thus, the MAC protocol as executor of TDMA in the upstream of the PON is of prime importance for cost effectiveness, fairness, traffic profile control, and quality of service (QoS) guarantees [3–5].

The work presented in this article was carried out in the framework of the GigaPON Access Network (GIANT) project [6], which is funded by the European Union Information Society Technologies (IST) Program. The project targets the design, implementation, and demonstration of a packet-based gigabit-per-second PON system. It supports all kinds of services featuring a wide range of QoS requirements, from very strict to plain best effort. The studies of the GIANT project have heavily influenced Alcatel's contributions to the FSAN initiative, but are also in turn aligned to FSAN standardization decisions as they become available.

GPON Operation

Conceptually, the TDMA operation in the upstream direction of a GPON is shown in Fig. 1. To guarantee collision-free transport and create common timing for the upstream frame, a ranging procedure during activation and registration measures the distance differences between the OLT and each ONU [3]. Thus, the ONUs at the customer side can calculate the start of each upstream frame as a fixed time distance after the arrival of the strictly periodic downstream frame. Then, under guidance of the global MAC controller, which grants access allocations that are fair and compatible, the available bandwidth can be almost fully exploited for alternate transmissions from the ONUs without overlaps. A small guard band as well as the necessary synchronization preambles (forming the so-called physical layer overhead upstream, PLO_u in FSAN terminology) is always found at the head of each upstream burst [3]. Optional blocks serving several functions may be marshaled in the frame under the command of the MAC controller, as elaborated in the next section. Such blocks are the power leveling sequence (PLS_u),physical layer operations, administration, and maintenance ($PLOAM_u$), and dynamic bandwidth report (DBR_u). (The subscript u indicates the direction i.e. upstream.) The allocations of the MAC controller are based on reports of the status of all ONUs' queues that are occasionally sent embedded in the upstream transmissions.

The GPON transmission convergence (GTC) specification (ITU-T draft G.984.3 [3]) defines, among other items, the framing format for both directions. In downstream, a fixed framing of 125 µs is used, allowing delivery of a synchronous 8 kHz clock. The system can be operated at several combinations of asymmetric or symmetric line rates, from 155.52 Mb/s to 2.48 Gb/s, to fit any operational situation. For the GIANT demonstrator, a symmetrical line rate of 1.24 Gb/s was chosen. The persistence of the 125 µs time reference gives away the importance still placed on the support of legacy time-division

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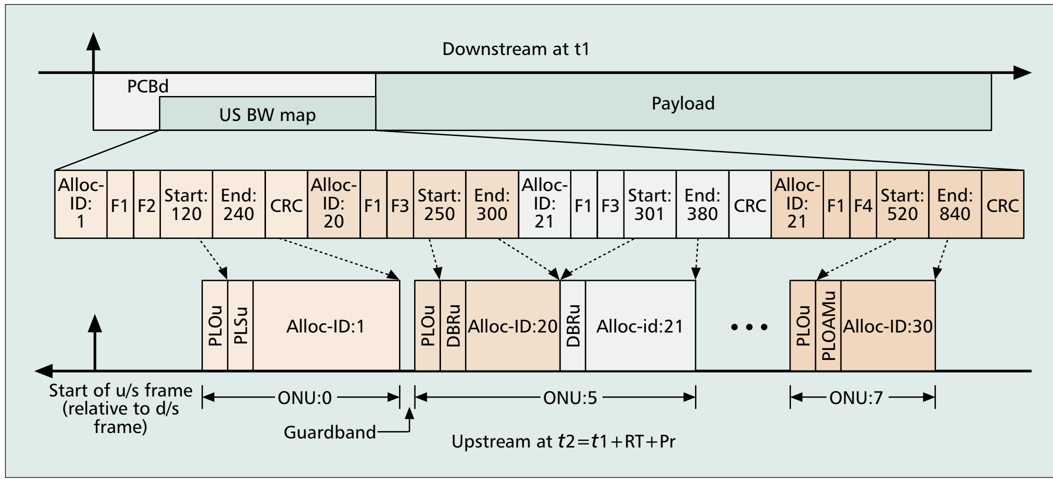

Figure 2. *The media access control concept.*

multiplex (TDM) services (e.g., virtual leased line service for small and medium enterprises), which are still significant for operator earnings. This and the optional support of ATM constitute an important advantage over the approach of the EFM EPON (Ethernet PON).

Another difference is found in the packet segmentation approach. In contrast to the IEEE EPON, the FSAN GPON does not transport Ethernet frames natively, but encapsulated using GPON Encapsulation Method (GEM) to enable fragmentation, which is not permitted in IEEE EPON. The latter transports only integral frames, which necessitates the reporting of individual packet lengths instead of queue lengths. To this end, a variable number of *queue sets*, each with a packet length from each queue, is sent upstream. This makes reporting more complex and elaborate, consuming more overhead, but in compensation this approach does away with the need for any reassembly of packets. The objectives of FSAN place more emphasis on accommodating TDM and ATM needs, leading to the adoption of fixed periodic framing so that services with very strict requirements can be serviced at the right moment, temporarily interrupting data packets; hence the need for fragmentation. A consequence of this is the need for an encapsulation method to allow extraction of variable length packets from fixed length frames and reconstruction of those spanning frame boundaries; this is done by GEM [3].

GPON Framing and MAC Control Fields

The periodicity of the downstream frame is the basis for keeping the timing relationships in the whole system. The format of the downstream frame starts with the physical control block (PCB_d), which features the following fields:

- A synchronization pattern as in any conventional fixed frame system (e.g., PDH, SDH)
- A 4-byte identifier containing a 30-bit frame counter incremented by 1 with every frame
- A 13-byte physical layer OAM message used to convey management information (e.g., alarms)
- 1 byte for bit interleaved parity (BIP), used to perform bit error rate estimation
- The upstream bandwidth (BW) map containing all the allocations for one upstream frame
- 4 bytes for payload length indicator ($Plen_d$), sent twice for reasons of robustness, which provides the length of upstream bandwidth (US BW) map and the size of the ATM segment

The MAC allocations dictate which queue of which ONU will send in each upstream frame, at what time and for how long. The BW map can be different in every frame in response to dynamic traffic fluctuations; this is the basis of the dynamic bandwidth allocation (DBA) [7]. How the MAC allocates upstream transmissions by means of the BW map is illustrated in Fig. 2, which shows a downstream frame at time t_1 and underneath the resulting upstream bursts from three ONUs (in this example, ONUs 0, 5, and 7) at some later time t_2 (which depends on the round-trip time, processing time, etc.). It is the job of the MAC controller to place inside the BW map the elements specifying the allocation after executing the bandwidth distribution algorithm. Each element (*access structure* in FSAN terminology) inside the US BW map specifies the queue of one ONU (identified by an Alloc-ID) and a pair of start and stop pointers, defining the variable time slot in which packets from the addressed Alloc-ID can be sent in the upstream. Each access structure is protected by a cyclic redundancy check (CRC) providing 2-bit error detection and 1-bit error correction.

A 12-bit flag field in each access structure includes four indications corresponding to grants for the addressed ONU to send the $PLOAM_u$, PLS_u, DBR_u, and forward error correction (FEC) overhead along with the real payload. (See examples of bursts in Fig. 2 and the detailed format of a full upstream burst in Fig. 3.) The flag field also specifies which of the three possible reporting modes (with corresponding length of 1,2, or 4 bytes) will be used in the DBA field of the DBR_u.

In response to the BW map allocations, the granted blocks will be sent in the upstream burst. The $PLOAM_u$ block contains the PLOAM mes-

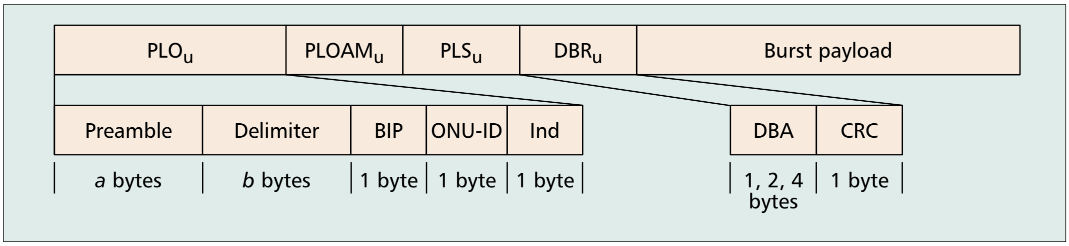

Figure 3. *Upstream GTC frame.*

sage as defined in G.983.1 [2]. The PLS$_u$ block is occasionally needed for power control measurement by the ONU. This function assists the adjustment of laser power levels to reduce optical dynamic range as seen by the OLT. When the ONU is FEC enabled, it will add a number of parity bytes behind every block of data, based on the RS(255, 239) encoding technique. Finally, the DBR$_u$ block includes the DBA field, which is used to report the status of the ONU queues to the MAC controller, on which the dynamic bandwidth allocation feature is based.

The DBA report implies a request to the MAC controller for an allocation of upstream transmission with as many bytes. So the DBA (along with the BW map) is the tool for reservation-based MAC; how reports are coded is described in the MAC operation below. Naturally, it is also protected by a CRC. Remember that in contrast to the above described overhead fields, which only appear in the upstream when granted through the flag bits, one type of overhead is always present at the start of an ONU upstream burst: the physical layer overhead (PLO$_u$), which contains the indispensable preamble, allowing proper PHY operation on the bursty upstream link.

The transmissions are assigned to each queue, uniquely identified by the Alloc-ID field. Each queue can aggregate streams per traffic class or be used for finer flow levels depending on implementation. Further multiplexing of traffic is possible based on GEM using the Port-ID field (just as the virtual path/virtual circuit, VP/VC, fields are used in the ATM part). A GPON can support almost 4000 Alloc-IDs with the 12-bit-long relevant field, but note that the first 254 Alloc-IDs are reserved as ONU identifiers, which are also used during the setup/activation of a (new) ONU.

Each burst payload consists of a variable number of GEM packets (as depicted in Fig. 4), each carrying either Ethernet traffic or TDM traffic. (If dual mode is supported, an ATM partition may be also present). The GEM packet consists of a 5-byte long header followed by a payload area of variable length. The GEM header contains:

- A payload length indicator (PLI) used for delineation
- A Port-ID that allows multiplexing of flows
- The payload type indicator (PTI), which shows if the fragment contains user data or OAM but also whether it is the last fragment of a user frame
- A HEC field for error detection and correction but also delineation

Whenever the GEM payload contains Ethernet encapsulated data, these can be either integral packets or fragments of packets depending on what fits in the allocated space, since the controller is not aware of packet boundaries, as this is not reported in the DBA fields.

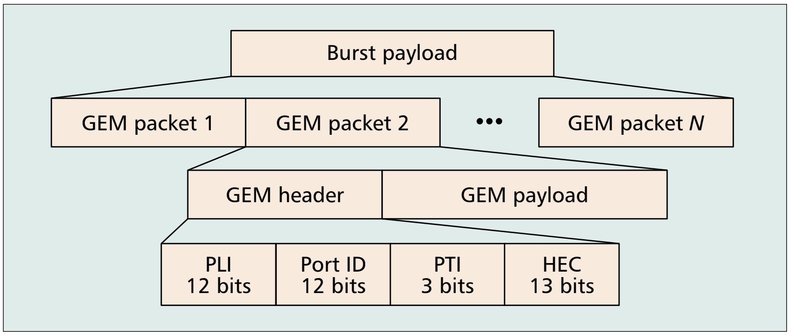

Figure 4. *FSAN GEM payload framing up/downstream.*

In the upstream direction, GEM frame delineation is performed based on "hunting" for the HEC field of a GEM header in all bit and byte alignments, using the GFP delineation algorithm specified in ITU-T G.7041 [8], which is a variation of the ATM delineation method. This algorithm uses the PLI in the GEM header to find the end of the GEM frame (since, unlike ATM, length is variable). The next GEM header should be found immediately after if alignment is correct. After recovering the GEM fragments, reassembly engines can reproduce all the frames on the basis of their Port-ID and the indication of last fragment in the PTI field.

The Dynamic MAC in Giant GPON

It is not in the scope of the FSAN draft to specify the MAC algorithm, since strict uniformity is not required for OLT–ONU interoperability. FSAN restricts itself to specifying the format of the exchanged information. The exact MAC allocation algorithm is left to the implementer. However, the definition of queue status reporting, access granting fields, as well as the traffic classes the standard imposes imply to a significant extent the MAC protocol mechanisms. Long experience from previous TDMA MAC protocols for APONs [4, 5, 7] has identified polling as the uncontested method for PON protocols. The bandwidth delay product of the GPON further precludes any collision resolution protocols, leaving as the only options reservation methods or pre-arranged unsolicited allocations emulating leased line services as in [2].

Regarding QoS support, the FSAN philosophy seeks to control each traffic stream by means of the MAC protocol to be able to effect the

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SLA and provide the required quality per user and stream, which explains the high number of traffic identifiers supported (4000). To this end, logically separate queuing is employed for each flow in each ONU down to a fine level of resolution (by means of Port-ID and Alloc-ID). The quality class, and hence the service received, are determined by assigning each queue (i.e., Alloc-ID) to one of five traffic containers (T-CONTs) that follow different service policies. In contrast, the EFM P2MP protocol uses eight queue classes corresponding to the quality discrimination tools recently introduced into Ethernet bridging (e.g., IEEE802.1p and IEEE802.1Q).

The five traffic classes of FSAN are a legacy from the APON DBA specification G.983.4 [7] keeping the same term: T-CONT. However, the descriptors of each T-CONT must now include, apart from the service interval, the duration of the allocated upstream bursts from each queue (i.e., Alloc-ID) as required to handle variable length packets.

◊ T-CONT1 service is based on unsolicited periodic permits granting fixed payload allocations. This is intended for the emulation of leased line services and the support of constant bit rate (CBR)-like applications with strict demands for throughput, delay, and delay variation. This is the only static T-CONT not serviced by DBA.

◊ T-CONT2 is intended for variable bit rate (VBR) traffic and applications with both delay and throughput requirements, such as video and voice. The availability of bandwidth for the service of this T-CONT is ensured in the SLA, but this bandwidth is assigned only on request (indicating the existence of packets in the queue) to allow for multiplexing gain.

◊ T-CONT3 is intended for better than best effort services and offers service at a guaranteed minimum rate; any surplus bandwidth is assigned only on request and availability.

◊ T-CONT4 is intended for purely best effort services (browsing, FTP, SMTP, etc.), and as such is serviced only on bandwidth availability up to a provisioned maximum rate.

◊ T-CONT5 is a combined class of two or more of the other four T-CONTs to remove from the MAC controller specification of a target T-CONT when granting access. It is now left to the ONU to choose which queue to service. Adopting this approach (sometimes referred to as using *colorless grants*) is left to the system designer.

The operation of the MAC algorithm uses the regular reporting of the queue lengths. However, the draft allows for non-status reporting ONUs as the default case; then the MAC controller is left to surmise the status of waiting traffic by empty arriving slots. This requires the MAC to drive the queues to exhaustion, and some inefficiency is the inevitable penalty of such an approach. When DBA is adopted, the reporting can be done either in the DBA field of DBRu (called piggyback reporting because the requests travel along with the payload in the burst) or by a whole ONU DBA report in which reports are carried in a dedicated partition of the payload section. The rationale of the latter is to provide enough space to report any number of ONU queues, even all if wished. Piggyback DBA reporting can be done in one of three modes:

◊ Mode 0 uses single-byte reports that give the queue length expressed in ATM cells (for ATM transport) or 48-byte blocks (for GEM). This mode is obligatory for status reporting ONUs, while the other two are optional.

◊ Mode 1 uses two bytes; the first reports the amount of data with peak rate tokens, the second those with sustainable rate tokens. This mode is useful for T-CONT types 3 and 5, and presumes policing units in the ONU that check compliance using a token bucket.

◊ Mode 2 uses 4-byte reports. The first byte reports T-CONT2 cells with peak rate tokens, the second T-CONT3 with sustainable rate tokens, the third T-CONT3 with peak rate tokens, and the fourth the T-CONT4 queue length (best effort). This mode is useful for the T-CONT5 approach in which a summarized reporting of all the subtending T-CONTs of an ONU can be sent in a single message.

In all modes nonlinear coding is used in queue length reports above 128 (see details in [3]) similar to that used in the ATM DBA [7]. The GIANT MAC supports only mode 0.

Equipped with a collection of queue lengths mirroring the global queuing situation in the GPON (albeit with a certain delay reflecting an earlier epoch), the MAC controller executes the assignment of both the guaranteed and surplus parts of the bandwidth to the active queues. In addition to the queue reports, which reflect the temporal properties of the traffic and change dynamically, the MAC also takes into account the service level parameters that govern the long-term limits of traffic. The latter are negotiated during the service activation and provided by means of management tools during service provisioning.

The service principle is a prioritized weighted round-robin. The priority order is, of course, T-CONT2 first, then 3 and 4, while the weights follow SLA parameters. Each flow is identified by its Alloc-ID and associated with one ONU. It belongs to one T-CONT type and is characterized by two parameters: successive data interval (SDI) and transmit bytes (TB). Upper and lower bounds of these parameters are defined in the SLA. This provides the tool to specify a guaranteed part (based on minTB, MaxSDI) allowing the surplus bandwidth to be assigned dynamically up to the peak rate (defined by MaxTB, MinSDI) by properly varying the actual values of TB and SDI in each allocation. The MAC controller in GIANT uses the SDI timers to space the allocations to each queue, while relying on DBA to decide how many bytes to grant (but in any case less than MaxTB) in each allocation by inspecting the request table where past unserviced requests are stored, reflecting the queue fill level. The examination of this table follows the round-robin discipline. Note that the overall server is not work-conserving as it tries to regularly space by SDI the bursts from each Alloc-ID to avoid creating excessive packet clusters that violate traffic contracts.

More specifically, for T-CONT1 the maximum and minimum TB and SDI values are equal (to keep delay variation zero). The same is true for T-CONT2, but now the respective allocations are issued on the basis of DBA (i.e., only on condition of request existence). For T-CONT3, maximum and minimum values are differentiated, resulting in the differentiation of guaranteed and surplus bandwidth assignment, while for T-CONT4, the maximum grant interval is infinite, providing no guarantees.

Polling is used to give a chance to send a piggyback report whenever no outstanding requests are found in the request table for an Alloc-ID. In other words, the maximum permissible SDI is used to set the next service interval for a queue appearing empty in the request table (but which may not be empty anymore due to recent and as yet unreported arrivals). It is worth mentioning that the polling frequency is a critical parameter on DBA performance, since it sets an upper limit to the service time, after adding the round-trip for reservation and the processing time. For example, in order to satisfy the maximum of 3 ms delay budget for real-time services, a maximum polling interval of 500 µs has to be adopted to guarantee an access delay below 1.5 ms in all traffic situations.

MAC PERFORMANCE

Brief representative simulation results are presented below to give the reader an impression of how a typical GPON MAC, which follows the FSAN approach, behaves. The MAC mechanism employed is the one described above, which is currently under field programmable gate array (FPGA) implementation in the IST GIANT project. The rate is *1.24416 Gb/s* symmetrical [6]. Since the performance of T-CONT1 is quite predictable due to the service strategy employed (unsolicited grants of fixed size and interval), it was not included in the scenarios. The OPNET simulation tool was used to prepare the model of the system consisting of 32 ONUs, each capable of establishing up to six queues (Alloc-IDs). The sources used in the two scenarios presented use the trimodal packet size traffic generation pattern; that is, packet sizes equal to 64, 500, and 1500 bytes are generated with probability 0.6, 0.2, and 0.2, respectively, reflecting often reported Internet traffic observations. The interarrival time is exponential. It is worth pointing out the difficulty in quoting net system capacity of the upstream system due to the variable nature of the overhead, which depends on the percentage of the several types of blocks that can be present. However, the average net capacity is close to 1 Gb/s ,and this value is used as a reference.

For the first scenario, the total offered load is *690 Mb/s* (i.e., nearly 70 percent of the net GPON capacity). One source per ONU injects T-CONT2 traffic at *7.1875 Mb/s* mean rate. Similarly, one 7.1875 Mb/s source per ONU is used for T-CONT3 and the same one for T-CONT4. The probability density function (pdf) of access delay is shown in Fig. 5 for the three queues (T-CONT2, 3, 4) of one ONU. As expected at such loads, all queues are serviced with very small delay on average, but the probability of high values reduces dramatically from T-CONT4 to 3 and 2, as does the range of observed values (delay variation) due to the different guaranteed parts and corresponding priorities.

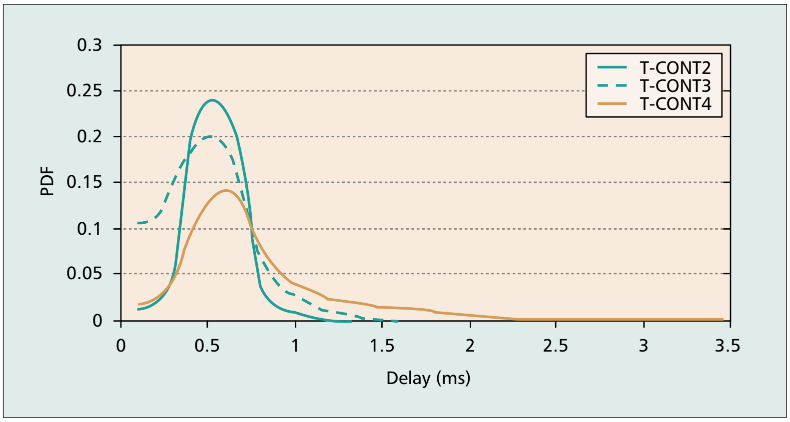

Figure 5. *Probability density function of access delay at approximately 70 percent load.*

It is interesting to observe what happens if the total load exceeds net capacity, and this is shown in the next scenario at an offered load of 1300 Mb/s (approximately 130 percent of capacity). Each ONU is now injecting 12.5 Mb/s of T-CONT2, 12.5 Mb/s of T-CONT3, and 15.625 Mb/s of T-CONT4 traffic. The performance results are depicted in Fig. 6. T-CONT2 and T-CONT3 enjoy good performance, leaving T-CONT4 to suffer congestion and instability. Attention is drawn to the two different scales. In any case, both T-CONT2 and 3 experience delays below 1 ms, which easily satisfies the 3 ms round-trip delay budget mandated by FSAN for demanding real-time services.

It is worth mentioning that although in this simulation model the delay of T-CONT4 increases toward infinite, in real life TCP closed loop flow control mechanisms would jump into action at the detection of loss and reduce the source transmission rate, restoring queue stability. However, it is meaningless to include TCP action in the model and simulate a closed loop scenario where the behavior of the rest of the network would be the dominant aspect, when we are only interested in evaluating the performance of the GPON MAC without interference from the overall network model. The important observation is that T-CONT2 and 3 traffic performance does not depend on the total system offered load as is necessary to provide QoS guarantees, while T-CONT4 service depends on the availability of unassigned bandwidth and is dynamically serviced. A service level agreement, including admission control and policing, would disallow overloading for T-CONTs 1, 2, and 3, while TCP mechanisms would take care of the non-guaranteed T-CONT4 part.

As regards jitter, the difference between T-CONT2 and 3 is very small; only the initial transient, left on purpose, is a bit higher. It is worth noting that the jitter of T-CONT2 is kept low despite the wildly varying packet length, which is compensated by the variable length grants of the MAC. It would be even lower under a smoother traffic generation process more realistically matching the nature of T-CONT2 services, which are rather more streamed than the trimodal model implies.

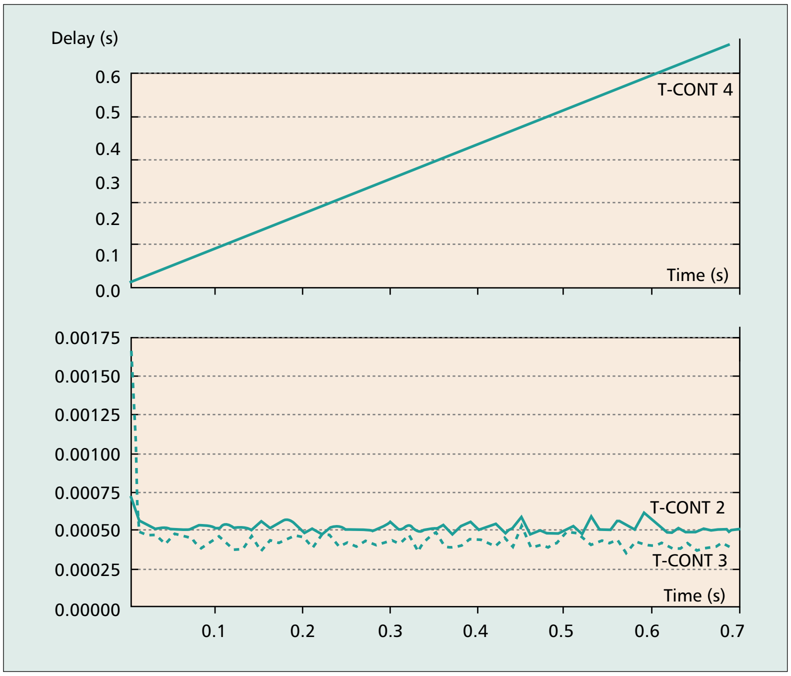

Figure 6. *System performance under overload.*

CONCLUSIONS

The standardization of GPONs transporting Ethernet-encapsulated data and supporting QoS-demanding services is a catalyst for widespread deployment of fiber in the local loop. The MAC protocol of such GPONs dictates the multiplexing policy, and consequently the efficiency and quality guarantees. Prioritized access of traffic aggregates having similar requirements is the key to satisfying quality with efficiency. On the other hand, the capability to control allocations down to a fine level of flow resolution provides the flexibility needed in order to enforce service level agreements, and realize present and future operator policies. All these features are combined in the presented MAC, which follows the FSAN philosophy into a system offering at once the 1.5 ms access delay guarantee for demanding services and high system utilization for less demanding services, albeit at the cost of higher delay. The MAC policy, although transparent, works in synergy with the service level specifications from which it draws the parameters that govern the allocations, achieving an overall balanced and effective result.

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BIOGRAPHIES

JOHN D. ANGELOPOULOS [M] received a Dipl.-Ing. degree from the National Technical University of Athens (NTUA), Greece, in electrical engineering (July 1973), an M.Sc. degree from Nottingham University, England, in automatic control, and a Ph.D. degree from NTUA on broadband telecommunications. From 1977 to 1989 he worked for the R&D section of Hellenic aerospace and telecommunication industries, at first in product development and later in engineering management. He was involved in the design and development of military switchboards, encryption equipment, and fire control computers. He also participated in national and European research projects in the fields of control and communications. In 1989 he turned to an academic career joining the Technological Institute of Piraeus where he is currently a professor in the Automation Engineering Department. He is in parallel participating in NTUA research activities in the areas of high-speed networks. He has been involved in RACE, ESPRIT, ACTS, and IST projects relating to MANs, ATM, and optical networking. His research interests include MAC protocol design for shared medium access systems, hardware and firmware for high-speed communications, passive optical networks, and optical packet switching. He is a member of the Technical Chamber of Greece.

HELEN-C. LELIGOU (nelly@telecom.ntua.gr) received her Dipl.–Ing. degree from NTUA, Greece, in electrical and computer engineering in 1995 and her Ph.D. degree from NTUA in broadband networks. Her Ph.D. thesis was in the area of access control mechanisms in broadband networks. She is involved in the research activities of the Telecommunications Laboratory in NTUA investigating access mechanisms for high-speed networks. She has designed and implemented MAC protocols for HFC systems and WDM metro networks of ring topology as well as scheduling components for a protocol processor environment in the framework of European projects. Her current research interests include access mechanisms for Gigabit PON systems. She is a member of the Technical Chamber of Greece.

THEODORE ARGYRIOU obtained his diploma in electrical engineering and computer science from the Faculty of Electrical and Computer Engineering of NTUA. He specialized in telecommunications, and his diploma thesis concerned the development and design of wireless networks and more specifically of DECT system. He is also a member of the Technical Chamber of Greece. He is interested in the design and implementation of network protocols especially in the area of photonics, and is also a postgraduate student in the M.B.A. course of NTUA.

STELIOS ZONTOS received his diploma in electrical engineering and computer science from the University of Patras, in 2001 and is currently a Ph.D. student. He specializes in cryptographic algorithms as well as in implementation of security systems in FPGAs. He has worked on protocol design and implementation in specification languages. Current interests include MAC protocols design and implementation, functionality and design of switching techniques, and research on optical networks.

TOM VAN CAENEGEM (tom.van_caenegem@alcatel.be) received an M.Sc. degree in physical engineering from Ghent University in 1995 and a Ph.D. degree in electrotechnical engineering in 2001, also from Ghent University. In 2001 he joined the Optical Access networks group in the Research and Innovation Center of Alcatel Bell, Antwerp, Belgium. Since the beginning of 2002, he is active as a systems engineer specializing in packet-based PON access, and contributing toward the Ethernet GPON proof of concept, with a GPON prototype demonstration to take place in 2004.