Resource Management for Broadband Access over Time-Division Multiplexed Passive Optical Networks

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Abstract

Passive optical networks are a prominent broadband access solution to tackle the "last mile" bottleneck in telecommunications infrastructure. Data transmission over standardized PONs is divided into time slots. Toward the end of PON performance improvement, a critical issue relies on resource management in the upstream transmission from multiple optical network units (ONUs) to the optical line terminal (OLT). This includes resource negotiation between the OLT and the associated ONUs, transmission scheduling, and bandwidth allocation. This article provides an overview of the resource management issues along with the state-of-the-art schemes over time-division multiplexed PONs (TDM-PONs). We categorize the schemes in the literature based on their features, and compare their pros and cons. Moreover, we introduce a unified state space model under which all TDM-PON resource management schemes can be evaluated and analyzed for their system level characteristics. Research directions are also highlighted for future studies.

Access networks are part of the telecommunications infrastructure that connect individual subscribers to the service provider's central office (CO) over public ground. They are cost prohibitive and have consistently been regarded as the bottleneck, primarily because the ever-growing demand for higher bandwidth is beyond the supported levels of the widely deployed access technologies. As illustrated in Table 1, the typical broadband access connections at home are composed of at least three phone lines, two high-definition television (HDTV) channels, and two PC connections for Internet access [1]. Neither digital subscriber line (DSL) nor cable modem can successfully meet the bandwidth requirements of this so-called "telhome" service. Therefore, upgrading access networks with a low-cost and high-capacity solution is necessary to provide broadband access.

As an inexpensive, simple and scalable technology, passive optical networks (PONs) are considered a promising solution to provide various end users with broadband access [2]. As exemplified in Fig. 1, a PON system is composed of one optical line terminal (OLT) residing in the central office (CO), one passive optical splitter deployed in the remote node (RN), and multiple optical network units (ONUs) near subscribers' locations. Intermediate powering between the OLT and the ONUs is eliminated by the use of optical fibers and passive optical splitter. Great efforts to push the PON standardization progress have been made through both the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) and the IEEE Ethernet in the First Mile Task Force (IEEE EFM TF). The ratified PON standard and recommendations are tabulated in Table 2. Significant differences among diverse PON "flavors" include the supported line rates and type of bearer units. The ITU-T G.983.x Recommendation series were ratified to specify broadband PON (BPON) [3], which employs asynchronous transfer mode (ATM) cells to encapsulate the data transmitted between the OLT and ONUs. IEEE 802.3ah [4] specifies the physical and medium access control (MAC) layer characteristics of Ethernet PON (EPON). EPON carries Ethernet frames with 1 Gb/s symmetric transmission speed. The recently approved IEEE P802.3av Task Force is working on an enhanced version of EPON, 10 Gb/s EPON (10GEPON). 10GEPON upgrades the existing EPON with two solutions, a symmetric solution of 10 Gb/s upstream and 10 Gb/s downstream transmission, and an asymmetric solution of 10 Gb/s downstream and 1Gb/s upstream transmission [5]. Gigabit PON (GPON) [6] is the continuation and evolution of BPON. Besides ATM cells, GPON supports Ethernet frames as well as time-division multiplexing (TDM) units by mapping them into GPON encapsulation method (GEM) frames. The maximum transmission speed over GPON reaches 2.448 Gb/s symmetrically.

BPONs, EPONs, and GPONs are also called TDM-PONs for their data transmission is divided into time slots. As shown in Fig. 1a, in the downstream from the OLT to the associated ONUs, one wavelength is employed, and TDM enables data transmission to different ONUs. This is a point-to-multipoint architecture, and data are broadcast to each ONU through the shared downstream trunk.

In the upstream direction from the ONUs to the OLT,

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another wavelength is employed. As shown in Fig. 1b, each ONU transmits the subscribers' data in dedicated time slots. This is a multipoint-to-point architecture, which requires a proper mechanism of access control on the shared wavelength. Because of the directional nature of the splitter, each ONU transmits directly to the OLT, but not to other ONUs. Therefore, the ONUs are unable to detect data collision in the upstream direction, and the conventional contention-based mechanism for resource sharing such as carrier sense multiple access with collision avoidance (CSMA/CA) and carrier sense multiple access with collision detection (CSMA/CD) is difficult to implement in TDM-PONs.

Network providers target to build access networks with the lowest cost while achieving the finest granularity. Because neither the EPON standard nor the BPON and GPON recommendations specify any particular resource management mechanism, upstream resource sharing is a critical issue for TDM-PON performance. Intensive research endeavors have been devoted to it recently. It is the purpose of this article to provide an overview of the resource management issue over TDM-PONs along with the state-of-the-art schemes. Although most of the schemes in the literature address EPON resource management, they can easily be extended to both BPON and GPON scenarios by employing appropriate medium access control (MAC) cells and fields in the frames.

The rest of the article is organized as follows. We describe the resource management issue by surveying the schemes of negotiation, scheduling, and bandwidth allocation. We evaluate different resource management mechanisms in a unified model, revealing their characteristics at the system level. Future research directions are highlighted later, and conclusions are drawn in the last section.

Connection	Number of connections	Bandwidth per connection
Phone	≥3	~64 kb/s
HDTV	≥2	~8 Mb/s
PC	≥2	~1 Mb/s

Table 1. *Bandwidth comsumption of telhome [1].*

Resource Management

Resource management over TDM-PONs aims to utilize the shared upstream wavelength as much as possible. The general guideline is to arbitrate the upstream transmission among the associated ONUs in a cost-effective manner. This can be achieved by the following: first, resource negotiation between the OLT and ONUs to facilitate dedicated and flexible time slot assignment; second, upstream scheduling to decide transmission order; third, upstream bandwidth allocation to arbitrate time slot length. An efficient resource management mechanism synergizes the above three processes.

Resource Negotiation

Resource negotiation exchanges information between the OLT and ONUs. TDM-PON MAC defines particular control messages, cells, or frame fields to enable the negotiation process.

In BPON, the 53-byte physical layer operation, administration, and maintenance (PLOAM) cell is employed to carry the negotiation information. In particular, one ONU embeds its queue status into the upstream PLOAM cell, indicating its request for the next transmission. The OLT notifies its associated ONUs of the resource arbitration decision by sending a 53-byte downstream PLOAM cell, which carries the grants made by the OLT. A grant is a permit from the OLT to

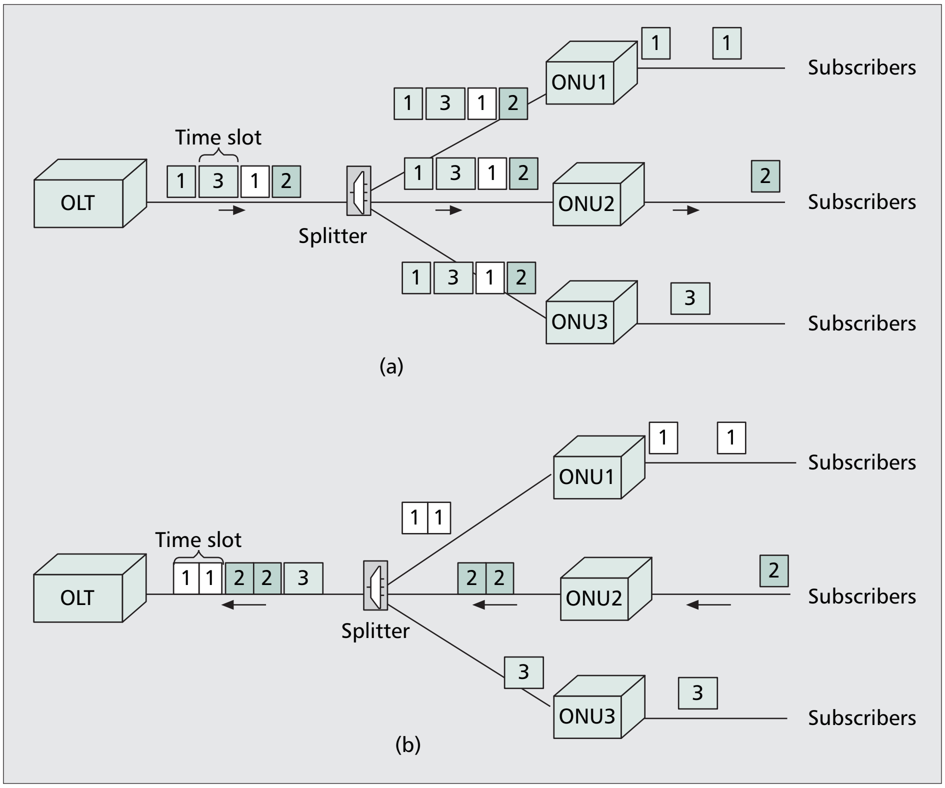


Figure 1. *Data transmission over EPONs: a) downstream; b) upstream.*

ONUs, informing them of the starting time and duration of their upstream data transport.

IEEE 802.3ah defines the multipoint MAC sublayer to manage the real-time manipulation over EPON. Multipoint Control Protocol (MPCP) is introduced to support resource negotiation between the OLT and ONUs. Two 64-byte MAC control messages are designed for this purpose. The REPORT message is generated by one ONU to report the queue status to the OLT. The OLT uses the requested information on queue status contained in the REPORT message to set up the upstream transmission. The GATE message is then generated by the OLT and sent downstream, broadcasting the arbitration decision.

In GPON, an ONU reports its transmission request by using the dynamic bandwidth report upstream (DBRu) field to indicate the queue status. In the downstream, the resource allocation information is carried by the physical control block downstream (PCBd) field. PCBd is transmitted at the beginning of each 125 µs GPON frame, notifying the ONUs of the upstream transmission assignment.

As shown in Fig. 2a, one way to conduct resource negotiation is to dedicate a very short timeslot for transferring the resource request from one ONU to the OLT. This implies twice laser on/offs for one upstream transmission from each ONU. The other scheme piggybacks the transmission request at the end of a timeslot [7]. This reduces laser on/off times into one per transmission per ONU. The piggybacked scheme saves the related overhead on physical layer power leveling, interframe guard, as well as laser control, and is widely used in TDM-PON resource management.

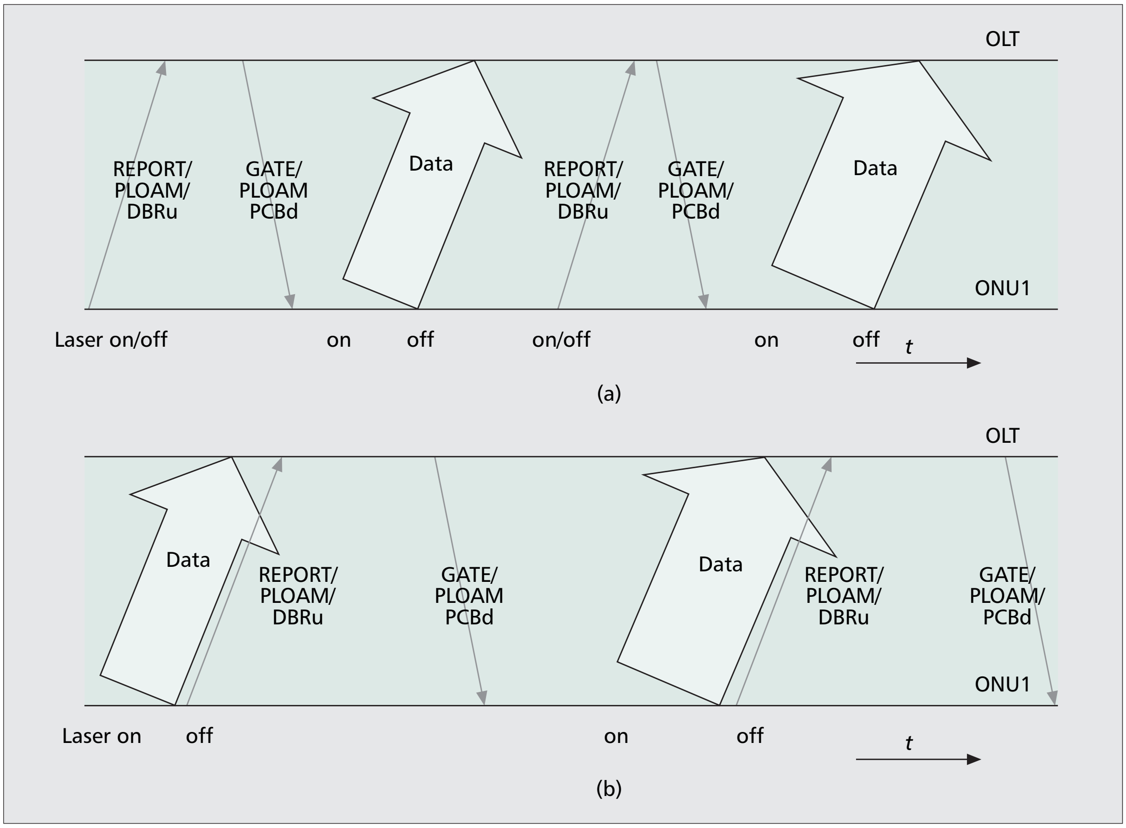
	BPON	EPON	GPON
Standard	ITU-T G.983.x	IEEE 802.3ah	ITU-T G.984.x
Maximum speed	1.244 Gb/s downstream 622.08 Mb/s upstream	1 Gb/s symmetric	2.448 Gb/s symmetric
Data unit	ATM cell	Ethernet frame	GEM frame, ATM cell

■ Table 2. *PON standards and recommendations.*

Upstream Scheduling

Inter-ONU Scheduling — The scheduling issue over TDM-PONs deals with arbitrating the transmission order among ONUs or different traffic in a transmission cycle. Round-robin (RR) scheduling [8] decides the ONU transmission order based on their identifications (IDs), which are assigned by the OLT when registering to a TDM-PON. Although RR is simple to implement, it is not adaptive to instantaneous changes of loaded traffic.

Zheng and Mouftah [9] addressed this issue by proposing two adaptive scheduling schemes: longest-queue-first (LQF) and earliest-packet-first (EPF). Because a longer queue usually leads to longer delay and higher packet lost probability, LQF schedules the transmission order of the ONUs in a TDM-PON based on the queue length. In each transmission cycle, the ONU with the longest queue has the highest priority to access the shared upstream trunk. The intuition behind LQF is to alleviate the average delay and packet loss by serving the heavily loaded ONU as soon as possible. On the other hand, EPF checks the timestamp of the first packet in each ONU's queue, and schedules the queue with the earliest first



■ Figure 2. *Resource negotiation over TDM-PONs: a) dedicated request; b) piggybacked request.*

Algorithm	Category	QoS support	Delay	Bandwidth utilization	Brief description
FBA [8]	FBA	No	High	Low	Both time slot length and transmission order are fixed; easy to implement; low utilization
IPACT [14]	IBA	No	Medium	Medium	REPORT/GATE mechanism for bandwidth negotiation; bandwidth allocation is upper bounded by SLA; flexible time slot length
FSD-SLA [15]	IBA	Yes	Compatible with IPACT	Compatible with IPACT	Bandwidth requirement is fulfilled by the SLA priority; fair allocation with max-min
COPS [12]	IBA	Yes	Higher than IPACT	Higher than IPACT	Class-of-service-oriented manipulation by using two groups of leaky bucket credit pools
HGP [11]	IBA	Yes	50 percent less than IPACT for EF data	Higher than IPACT	Each transmission cycle is divided into EF subcycle (ahead) and AF/BE subcycle (afterward) to transmit the differentiated data
Byun *et al.* [16]	PBA	No	Lower than FBA and IPACT	Higher than FBA and IPACT	A constant control gain is used to estimate the waiting time data
DBA1 [7]	PBA	Yes	Lower than FBA and IPACT	Higher than FBA and IPACT	The waiting time EF data are estimated by using the actual data in the previous cycle; AF and BE traffic are treated by IPACT
LSPT [17]	PBA	Yes	Lower than FBA and IPACT	Higher than FBA and IPACT	EF, AF, and BE data in the waiting time are estimated by using adaptive filters

■ Table 3. *Comparisons of bandwidth allocation algorithms.*

arriving packet first. EPF treats the timestamp of the first packet in a queue as the "life-to-live" of the queue. Since the older queue usually causes higher delay and loss, EPF essentially gives the highest priority to the oldest data.

Assi *et al.* [7] proposed to divide the ONUs into two groups: lightly loaded ONUs and heavily loaded ones. Data to be transmitted at the lightly loaded ONUs are less than or equal to the transmission upper bound. The OLT treats these ONUs as well behaved, and schedules their upstream transmission immediately after receiving the requests. Because heavily loaded ONUs' requests go beyond their bounds, the OLT schedules their transmission after lightly loaded ones. The OLT also calculates the surplus bandwidth from the lightly loaded ONUs and distributes it among the heavily loaded ones. This scheduling scheme rewards *obedient* ONUs with shorter delay, while penalizing *aggressive* ONUs with deferred service.

Ma *et al.* [10] proposed a multiple-access scheduling scheme to provide bandwidth-guaranteed service for high-demand ONUs, while serving low-demand ONUs with best effort service. The scheme begins with parameter-based call admission control, which categorizes ONU requests into a bandwidth guaranteed (BG) ONU group and a non-BG ONU group. An entry table for BG ONUs is established through the even distribution algorithm (EDA), and the OLT schedules BG ONUs by entry sequence. Non-BG ONUs are inserted into the empty entries of the table, and are served dynamically.

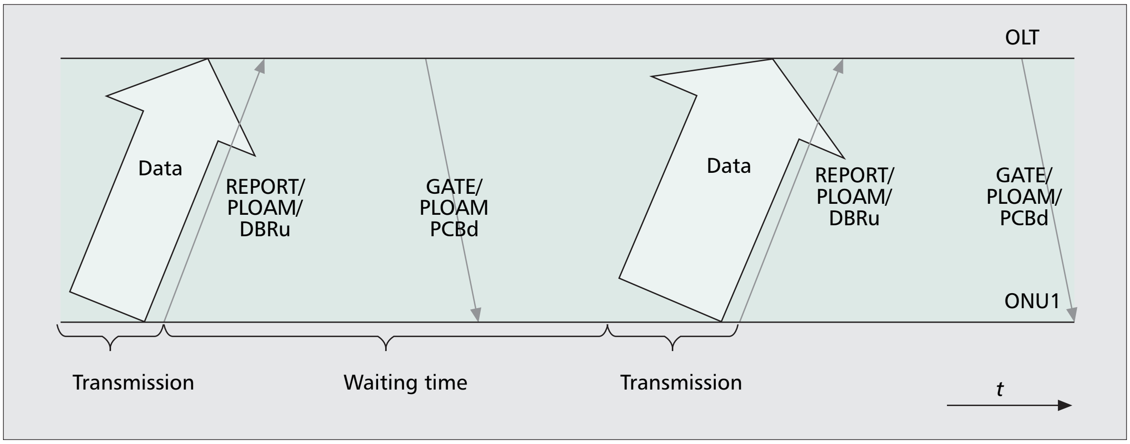
Intra-ONU Scheduling — Besides inter-ONU scheduling, tremendous research efforts have been devoted to intra-ONU scheduling [7]. Hybrid Granting Protocol (HGP) [11] classifies the data of each ONU into expedited forwarding (EF), assured forwarding (AF), and best effort (BE). Each transmission cycle is divided into two subcycles: EF and AF/BE. A transmission cycle begins by transferring the EF data from all ONUs to the OLT, followed by the AF and BE data.

Naser and Mouftah [12] further extended intrascheduling by incorporating the class of service (CoS) concept. In a TDM-PON with m ONUs, data to be transmitted are divided into n CoSs. The scheduler aggregates the data based on CoS, and delivers them in accordance with the CoS priority. Therefore, intra-ONU scheduling tackles diverse services by taking different requirements into consideration. It facilitates resource management over TDM-PONs in a service-oriented manner.

Bandwidth Allocation

In TDM-PONs, the OLT mandates upstream transmission by the employment of bandwidth allocation algorithms, targeting to improve the resource utilization. Many algorithms on bandwidth allocation have been proposed recently that are far beyond the scope reported in [13]. In the following, we provide a new perspective on the state-of-the-art progress in TDM-PON upstream bandwidth allocation. The major characteristics of the reviewed algorithms are summarized in Table 3. Various bandwidth allocation algorithms fall into three major categories: fixed bandwidth allocation (FBA), IPACT-based bandwidth allocation (IBA), and prediction-based bandwidth allocation (PBA). Based on whether they support QoS or not, some categories can be further classified into two subcategories.

Fixed Bandwidth Allocation — FBA grants one ONU a fixed time slot length for upstream transmission [8]. Without the overhead of resource negotiation as well as bandwidth arbitration, FBA is simple to implement. On the other hand, without considering the instantaneous changes of online traffic, FBA uses the upstream wavelength with low efficiency. For example, an ONU will occupy the upstream channel for its assigned time slot even if there are no data to transmit, while many data could be backlogged in the buffers of other ONUs. Kramer *et al.* [8] evaluated FBA performance, and concluded



■ Figure 3. *Waiting time in TDM-PON upstream transmission.*

that the low efficiency of FBA exacerbates data delay even under medium traffic load, and packet loss is thus deteriorated. Increasing the buffer size could not prevent this phenomenon, mainly because a larger buffer only slightly alleviates congestion, but continuously increases the burst delay, as more data are accumulated during the bursts.

IPACT-Based Bandwidth Allocation

IPACT — Interleaved Polling with Adaptive Cycle Time (IPACT) [14] is the first dynamic bandwidth allocation (DBA) algorithm proposed for TDM-PONs. IPACT adopts a resource negotiation process to facilitate queue report and bandwidth allocation. The OLT polls ONUs and grants time slots in a round-robin fashion. The granted time slot is determined by the queue status reported from the ONU. Therefore, the OLT is able to monitor traffic dynamics of each ONU and allocate the upstream bandwidth in accordance with traffic load. IPACT also employs the service level agreement (SLA) parameter to upper bound the allocated bandwidth to each ONU. This restricts the aggressive competition among ONUs for upstream transmission. As the pioneering bandwidth allocation algorithm, IPACT is regarded as the performance comparison benchmark by most later proposals.

IPACT with QoS — Realizing that IPACT alone could not fulfill the multiservice needs of subscribers, different IPACT variants were proposed with QoS provisioning. The state of the art includes the following algorithms.

Fair sharing with dual SLAs (FSD-SLA): The authors of [15] proposed to employ dual SLAs in IPACT. The primary SLA specifies the service whose minimum guarantee must be treated with high priority. The secondary SLA describes the service requirement with lower priority. This algorithm fulfills bandwidth allocation by first assigning timeslots to those services with primary SLA, guaranteeing their upstream transmission. After meeting services with the primary SLA, the next round is to meet the secondary SLA services. If bandwidth is not sufficient for the secondary SLA services, the max-min scheme is adopted to distribute the bandwidth with fairness. If surplus bandwidth is available after arbitration, FSD-SLA distributes the surplus portion first to the primary SLA entities, then to the secondary SLA entities, both by using max-min fair allocation.

Class-of-service-oriented packet scheduling (COPS): Naser and Mouftah [12] proposed the class-of-service-oriented packet scheduling (COPS) algorithm to tackle the multiservice issue. The basic idea is to maintain two groups of leaky bucket credit pools on the OLT side. One group includes k credit pools, corresponding to k CoSs in the TDM-PON system. Each pool is used to enforce a long-term average rate of certain CoS traffic transmitted from all ONUs to the OLT. The other group is composed of m credit pools, corresponding to m ONUs in the TDM-PON system. Each pool is used to control the usage of the upstream channel by an ONU. When processing bandwidth requests, the OLT begins with the highest-priority CoS of all ONUs to the lowest-priority CoS. As long as the OLT issues any grant, the granted bytes are subtracted from the corresponding credit pools. New requests will be granted as long as there are enough credits in the pools.

Hybrid granting protocol (HGP): Shami *et al.* [11] proposed the so-called hybrid granting protocol (HGP) to support diverse QoS requirements. HGP serves EF traffic in a deterministic manner, and AF and BE traffic with IPACT. One transmission cycle begins with the EF subcycle. The length of the EF subcycle is predetermined. The AF/BE subcycle follows the EF subcycle, and AF and BE traffic are transmitted according to the loaded data. In this way HGP guarantees the service of delay-sensitive EF traffic, while keeping QoS support for AF and BE services with flexible bandwidth allocation.

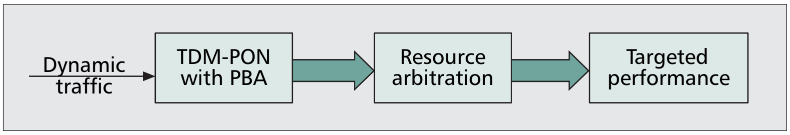
Prediction-Based Bandwidth Allocation (PBA) — As shown in Fig. 3, during upstream transmission each ONU experiences a waiting time that ranges from sending the transmission request to sending the buffered data. Since the reported queue status does not consider the data that have arrived in the waiting time, the OLT defers transmission of these data (also called waiting time data). To overcome this drawback, several PBA algorithms [7, 16, 17] have been proposed. The motivation is to achieve more accurate information about online traffic and deliver incoming data as soon as possible.

PBA without QoS — Byun *et al.* [16] addressed the aforementioned issue by estimating the waiting time data at an ONU and incorporating them into the grant to the ONU. More specifically, a control gain, α, is used to adjust the estimation based on the difference between the departed and arrived data in the previous transmission cycle. Simulations with $\alpha = 0.9$ show packet delay reduction from FBA and IBA.

PBA with QoS

Dynamic bandwidth allocation 1 (DBA1): Observing that delay-sensitive traffic is not able to afford waiting time deferral, the authors in [7] proposed an algorithm (DBA1) to estimate the waiting time of EF data by using the EF data that actually arrived in the previous transmission cycle. However, the authors did not consider the estimation of AF and BE traffic, which dominate the overall access network traffic load and exhibit more severe bursty characteristics.

Limited sharing with traffic prediction (LSTP): Luo and Ansari [17] proposed using an adaptive filter for traffic pre-



■ Figure 4. *PBA controllability.*

diction. The limited sharing with traffic prediction (LSTP) algorithm estimates each class of waiting time data based on data of this class that have actually arrived in previous transmission cycles. Therefore, the bandwidth requirement is the sum of the estimation and the reported queue length. The OLT arbitrates the upstream bandwidth by using this more accurate information. As a result, LSTP reserves a portion of the upstream bandwidth to deliver waiting time data in the earliest transmission cycle, thus mitigating delay and loss. By using different SLA parameters to restrict different classes of traffic, LSTP facilitates service differentiation.

State Space Representation: A General Evaluation Model

In order to provide a general representation of the resource management issue in TDM-PON upstream, a state space model was recently proposed [18]. This model describes the TDM-PON system as a threesome of online traffic load, bandwidth arbitration decision, and queue status at ONUs. The resource allocation of transmission cycle $(n + 1)$ is related to that of transmission cycle n by differential equations. This time domain approach provides a convenient and compact way to model and analyze the TDM-PON system with multiple inputs from and outputs to the associated ONUs.

System Model

As formulated in Eq. 1, no queue status report is conducted in FBA, and the reported queue length equals zero. In IBA the reported queue length of transmission cycle $(n + 1)$ is determined by the difference of the injected data, which include the transmission residual of cycle n (i.e., $Q_i(n)$) as well as the incoming data arrived in the waiting time at ONUi in transmission cycle n (i.e., $\lambda_i(n)$), and the delivered data (i.e., $d_i(n)$). In PBA it is possible for *over-grant* to occur. This over-grant is adjusted by reporting the difference between the injected data (i.e., $Q_i(n) + \lambda_i(n)$) and the grant $G_i(n)$.

$$Q_i(n+1)=\begin{cases} 0, & FBA \\ Q_i(n)+\lambda_i(n)-d_i(n+1), & IBA\ . \\ Q_i(n)+\lambda_i(n)-G_i(n+1), & PBA \end{cases} \tag{1}$$

The bandwidth request of ONUi in transmission cycle $(n + 1)$ (i.e., $R_i(n + 1)$) can be further represented as

$$R_i(n+1)=\begin{cases} B_{fix,} & FBA \\ Q_i(n), & IBA\ , \\ Q_i(n)+\hat{\lambda}_i(n+1), & PBA \end{cases} \tag{2}$$

where $\hat{\lambda}_i(n)$ is the predicted arrived data at ONUi in the waiting time of transmission cycle n.

The assigned bandwidth to ONUi in transmission cycle $(n + 1)$ (i.e., $G_i(n + 1)$) is the fixed value B_{fix} in FBA. In both IBA and PBA, it is the smaller value of the bandwidth request (i.e., $R_i(n + 1)$) and the SLA parameter (i.e., G_i^{max}), that is,

$$G_i(n+1)=\begin{cases} B_{fix,} & FBA \\ \min[R_i(n+1),G_i^{\max}], & IBA\ . \\ \min[R_i(n+1),G_i^{\max}], & PBA \end{cases} \tag{3}$$

After receiving the bandwidth allocation decision, ONUi schedules its upstream transmission indicated by $G_i(n + 1)$, and the delivered data $d_i(n + 1)$ are

$$d_i(n + 1) = \min\{G_i(n + 1), R_i(n) + \lambda_i(n)\}. \tag{4}$$

Different bandwidth allocation algorithms are investigated from the viewpoint of system control. They are put into the state space of Eq. 5, where $X_i(n) = [R_i(n), Q_i(n)]^T$ is the state vector, representing the bandwidth requirement and queue length report of ONUi, and $U_i(n)$ is the input vector, representing the arrived data and the SLA parameter.

$$X_i(n + 1) = AX_i(n) + BU_i(n). \tag{5}$$

Hence, Eq. 5 describes the upstream bandwidth allocation over a TDM-PON system, and a different algorithm essentially defines its particular coefficient matrices A and B to assign the upstream bandwidth in a different way.

Under a particular traffic load, the assigned bandwidth $G_i(n + 1)$ in Eq. 3 and delivered data $d_i(n + 1)$ in Eq. 4 are determined, and the system described by Eq. 5 falls into one of the following four scenarios:

Scenario 1: $R_i(n + 1) \le G_i^{max}$, $G_i(n + 1) > Q_i(n) + \lambda_i(n)$

Scenario 2: $R_i(n + 1) \le G_i^{max}$, $G_i(n + 1) \le Q_i(n) + \lambda_i(n)$

Scenario 3: $R_i(n + 1) > G_i^{max}$, $G_i(n + 1) > Q_i(n) + \lambda_i(n)$

Scenario 4: $R_i(n + 1) > G_i^{max}$, $G_i(n + 1) \le Q_i(n) + \lambda_i(n)$

Controllability

In scenario 1, the FBA algorithm blindly grants bandwidth B_{fix} to ONUi, and the system state space becomes

$$\begin{bmatrix} R_i(n+1) \\ Q_i(n+1) \end{bmatrix}=\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} R_i(n) \\ Q_i(n) \end{bmatrix}+\begin{bmatrix} 1 \\ 0 \end{bmatrix}B_{fix}. \tag{6}$$

This is a discrete linear system represented by $X_i(n + 1) = AX_i(n) + BU_i(n)$, where

$$A=\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, B=\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

and $U_i(n) = B_{fix}$. Its controllability matrix M is

$$m=\begin{bmatrix} B & AB \end{bmatrix}=\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}.$$

Based on controllability analysis [19], since the controllability matrix M is not full rank, the system represented by Eq. 6 is uncontrollable.

When an IBA system falls into scenario 1, $d_i(n + 1) = Q_i(n) + \lambda_i(n)$, and Eq. 1 yields $Q_i(n + 1) = Q_i(n) + \lambda_i(n) - d_i(n + 1) = 0$. Equation 2 further yields $R_i(n + 1) = Q_i(n)$, and thus the system turns into

$$\begin{bmatrix} R_i(n+1) \\ Q_i(n+1) \end{bmatrix}=\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} R_i(n) \\ Q_i(n) \end{bmatrix}+\begin{bmatrix} 0 \\ 0 \end{bmatrix}\lambda_i(n). \tag{7}$$

The controllability matrix M is

$$m=\begin{bmatrix} B & AB \end{bmatrix}=\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix},$$

and it is not full rank. Therefore, the TDM-PON system with IBA is uncontrollable in scenario 1.

Assume $\hat{\lambda}_i(n+1) = \alpha_i\lambda_i(n)$ is employed in PBA to estimate the data arrived in the waiting time. Scenario 1 implies an over-grant case, where $G_i(n+1) > Q_i(n) + \lambda_i(n)$ and the bandwidth request $R_i(n+1) = Q(n) + \hat{\lambda}_i(n) = Q(n) + \alpha_i\lambda_i(n-1)$. Since the request does not exceed $G_i^{\max}$, Eq. 3 yields $G_i(n+1) = R_i(n+1)$. Thus, Eq. 1 yields $Q_i(n+1) = Q_i(n) + \lambda_i(n) - R_i(n+1)$; that is, $Q_i(n+1) = Q_i(n) + \lambda_i(n) - \alpha_i\lambda_i(n-1)$. The state space thus becomes

$$\begin{bmatrix} R_i(n+1) \\ Q_i(n+1) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} R_i(n) \\ Q_i(n) \end{bmatrix} + \begin{bmatrix} 0 & \alpha_i \\ 1 & -\alpha_i \end{bmatrix} \begin{bmatrix} \lambda_i(n-1) \\ \lambda_i(n) \end{bmatrix}. \tag{8}$$

As proved in [18], the controllability matrix of the above state space is full rank, implying that a TDM-PON system with PBA in scenario 1 is controllable.

After evaluating all four scenarios for FBA, IBA, and PBA, it was pointed out that FBA is completely uncontrollable, IBA is partially controllable, while PBA is completely controllable [18]. A bandwidth allocation algorithm is said to be completely controllable if it is able to meet the dynamic traffic input from multiple ONUs, and steer the bandwidth efficiency over the applied TDM-PON system from an arbitrary state to the optimum state within a limited time. In other words, as shown in Fig. 3, a completely controllable algorithm is able to drive the TDM-PON system to the targeted performance by conducting proper resource management. For example, if we target less than 15 percent packet loss under traffic load 0.5, the implementation of PBA guarantees that we are able to satisfy this requirement, while neither FBA nor IBA can ensure this.

It is no surprise to see that FBA is completely uncontrollable, because it blindly allocates shared resources by ignoring traffic dynamics. Its uncontrollability also explains why, from the system's point of view, FBA generates the lowest resource utilization.

Partial controllability implies that IBA is unable to handle some circumstances over a TDM-PON system. For example, when one ONU consistently requests more bandwidth than it actually needs while other ONUs present their real transmission needs, IBA will grant excessive bandwidth to the over-requests. As a result, the shared upstream bandwidth will be wasted by idle time slots; thus, unfairness and underutilization occur. Partial controllability reveals, from the system's point of view, that a TDM-PON system with IBA could not effectively capture the dynamic changes of system state and input traffic. As a result, IBA is incapable of tuning the upstream resource allocation into the targeted state within a prescribed time window.

On the other side, PBA monitors the actual arrived data by checking $Q_i(n)$ and $\lambda_i(n)$, and the bandwidth arbitration decision is determined by both queue length and estimation. In this sense, any over-requesting ONU cannot idly and constantly occupy the upstream channel, and the allocated resource to each ONU follows its real traffic load. The reported simulation results show that PBA is able to manage the shared resources effectively [7, 16, 17].

Stability

Stability is meaningful only when a TDM-PON system with a particular bandwidth allocation algorithm is controllable. A bandwidth allocation algorithm is said to be *stable* if it is able to provide fair sharing of upstream bandwidth among ONUs when input traffic load changes. Following the state space model, stability analysis is applied to PBA [16]. Reference [20] evaluates the stability characteristics of PBA. For each scenario, a proper controller is required to drive the TDM-PON system with PBA into the stable state. This is known as *pole placement* [19]. The controller is represented as

$$U_i(n) = -KX_i(n), \tag{9}$$

where $X_i(n) = [R_i(n), Q_i(n)]^T$ is the state vector, and constant matrix K indicates the controller gain. As a result, the system of Eq. 5 with controller becomes

$$X_i(n+1) = (A - BK)X_i(n). \tag{10}$$

Jury's criterion [21] is the generally adopted guideline to derive controllers for a discrete system. In [20] controller design for each scenario has been investigated. This implies that in the TDM-PON system with PBA, the OLT manipulates upstream transmission from multiple ONUs by using a different controller under a different scenario. A particular controller could be facilitated through proper buffering and intra-ONU scheduling schemes at the ONU, or an appropriate inter-ONU scheduling scheme among ONUs. Implementing such controllers ensures that the upstream bandwidth of the applied TDM-PON system is fairly shared by ONUs.

Future Studies

Future research on resource management for broadband access could be steered in the following directions.

First, the pursuit of the optimum resource allocation solution could be approached by following the general state space model. This implies designing a resource management mechanism from the viewpoint of TDM-PON system control. Although the existing PBA proposals alleviate some of the problems involved in TDM-PON resource management, they may not be able to achieve the targeted performance fast enough. More transmission cycles may be experienced before the TDM-PON system reaches the desired state. Proper schemes for buffering and scheduling are key components of the optimum solution that could serve as guidelines to effectively direct the arbitration of upstream bandwidth among multiple ONUs.

Second, the resource management mechanism of TDM-PONs is expected to be extended into more diversified scenarios. For example, wavelength-division multiplexed PONs (WDM-PONs) [22] are deemed one of the next-generation fiber optic access technologies. Unlike in TDM-PONs, each ONU in a WDM-PON communicates with the OLT using a pair of dedicated wavelengths (one for downstream, the other for upstream). Future access networks are most likely to shift to a hybrid architecture of WDM and TDM, utilizing WDM technology to reach the curb and neighborhood, and employing TDM technology to reach the end users. Since access networks are extremely cost-sensitive, successful resource management migration is imposed to make the best use of low-cost TDM resources while reducing the system cost of the expensive WDM part.

The third direction falls into the synergy of optical and wireless technologies in access networks [23]. A proper resource management mechanism is necessary to integrate fiber capacity and wireless communication mobility. Related issues include:

- How to aggregate multiple wireless channels into one optical wavelength
- How to describe the wireless resource in the general model
- How to tackle wireless dynamics besides traffic dynamics
- How to reduce transmission overhead in the integrated platform

Conclusions

Resource management is critical to access network performance. In TDM-PONs, it implies dynamic information exchange between the OLT and ONUs, upstream transmission scheduling, as well as upstream bandwidth arbitration. In this article, following the introduction of challenges related to resource management over TDM-PONs, we provide an overview of the state-of-the-art proposals in the literature. The state space representation has been introduced as a general model to evaluate the reviewed proposals. Our discussion explains the performance differences among the major proposals from the perspective of system control. This analysis helps us to conduct further research in many emerging fields, including providing resource management guidelines, accommodating the WDM access challenges, and incorporating heterogeneous options for broadband access.

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TING WANG's biography was unavailable when this issue went to press.