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ORIGINAL ARTICLE

Supporting differentiated services with fairness by an urgency fair queuing scheduling scheme in EPONs

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Abstract The Ethernet Passive Optical Network (EPON) has recently attracted increasingly more attention from the industry since it could be a perfect candidate for next generation access networks. Supporting differentiated services in EPONs is an important issue for service providers to design an EPON system. A consequent interesting topic is how to achieve fairness among different users in EPONs. In this paper, we propose an Urgency Fair Queuing (UFQ) scheme to support Differentiated Services (DiffServ) among multiple users in EPONs. It can achieve fairness by allocating as much as possible bandwidth to best-effort traffic while guaranteeing the services for the Quality of Service (QoS) traffic streams simultaneously. The simulation results show that UFQ can effectively provide differentiated services for different types of traffic with fairness.

Keywords Ethernet passive optical network · Medium access control · Differentiated services · Quality of service · Fair scheduling

Introduction

Recently, industry has witnessed the rapid emergence and development of the Ethernet Passive Optical Network (EPON) as one of the best choices for next generation access networks, since it merges the virtues of inexpensive Ethernet equipment and high-bandwidth fiber transmission media [1, 2]. An EPON is a point-to-multipoint network consisting of an Optical Line Termination (OLT) and multiple Optical Network Units (ONUs), which are connected by a passive optical splitter. In the downstream direction (from the OLT to ONUs), data packets are broadcasted by the OLT to all ONUs. Each ONU extracts its data based on the Medium Access Control (MAC) addresses, and discards packets not destined to it. In the upstream direction of the EPON (from ONUs to the OLT), multiple ONUs contend for transmitting packets. To avoid conflicts, a multi access control protocol is required in the upstream direction to enable the transmission capacity to be shared by the ONUs efficiently [3]. The standard organization of EPONs, the IEEE 802.3ah Task Force, has developed a multipoint control protocol (MPCP) framework for MAC protocols used for upstream transmission in EPONs [4].

Supporting Differentiated Services (DiffServ) with various requirements is highly regarded as a substantial requirement for EPONs. Different types of incoming traffic can be mapped into the quality of service (QoS) or best-effort traffic according to their requirements. An EPON must be capable of classifying the traffic into classes and serving each class differently to meet the service requirements. The IEEE 802.1D standard together with its extensions P802.1p and P802.1Q, which are regarded as the QoS protocol on the MAC level, provides the related standard for EPONs [5]. Achieving fairness is one of the main objectives of the MAC layer scheduling schemes. The key issue is to allocate the remaining bandwidth to best-effort traffic while ensuring the requirements of different types of QoS traffic. Our main goal is to propose a scheme within the framework of IEEE

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802.1D, and study how this scheme can be combined with the limited transmission services to support DiffServ in the EPON system and simultaneously achieve fairness among different users.

A hierarchical scheduling architecture is adopted to effectively share the transmission link as well as to support DiffServ in EPONs, which consists of inter-ONU scheduling and intra-ONU scheduling. Inter-ONU scheduling deploys the multiple access schemes for bandwidth allocation among multiple ONUs within the MPCP framework. And intra-ONU scheduling adopts the mechanisms supported by IEEE 802.1D to provide differentiated services to different traffic streams in the same ONU.

In this paper, we propose an Urgency Fair Queuing (UFQ) scheme for intra-ONU scheduling in EPONs. It takes into account the QoS requirements of different traffic types and schedules packet transmissions in the same ONU according to their urgency. By assigning as much as possible bandwidth to best-effort traffic while providing the guaranteed services to the QoS traffic streams, UFQ can significantly improve the performance of best-effort traffic while satisfying the requirements of different QoS traffic simultaneously. Furthermore, it can achieve fairness among different traffic types and utilize the bandwidth efficiently. Inter-ONU scheduling adopts a similar efficient MAC protocol as we proposed in [7] for multiple ONUs sharing the upstream link without collision. Compatible with the MPCP, the protocol includes a parameter-based Call Admission Control (CAC) mechanism, the Evenly Distributed Algorithm (EDA), and the Bandwidth Guarantee Polling (BGP) scheduling scheme. It provides different services to different ONUs according to the Service Level Agreement (SLA) between the service provider and end users.

By combining the proposed UFQ scheme with the efficient MAC protocol, the hierarchical scheduling method can effectively provide differentiated services to different kinds of users. The rest of the paper is organized as follows. Section ‘Related work and motivation’ introduces other work related to the topic to motivate our study. Section ‘Hierarchical scheduling’ introduces the hierarchical scheduling configuration in the upstream transmission direction in EPONs. The inter-ONU scheduling protocol is described in section ‘Inter-ONU scheduling protocol’, whose kernel is the BGP scheduling scheme. Section ‘Intra-ONU scheduling scheme’ presents the UFQ scheme supporting DiffServ in intra-ONU scheduling. Experimental simulation results are shown in section ‘Simulation experiment’, and finally we get the conclusion in section ‘Conclusion’.

Related work and motivation

The hierarchical scheduling architecture is adopted in several papers [5, 6] for EPON upstream transmission, which deploys different schemes for intra-ONU scheduling.

Reference [5] uses Strict Priority Queuing (SPQ) and Two-Stage Queuing (TSQ) for intra-ONU scheduling. In the SPQ mechanism, packets in each ONU are transmitted strictly according to their priorities. The lower-priority traffic will only be served after the higher-priority traffic has been transmitted. Besides, a newly arriving higher-priority packet can replace lower-priority packets when the free space in the finite buffer is not large enough to accommodate it. Such a mechanism will result in performance polarization between different classes of traffic in the same ONU, where the higher-priority traffic gets better-than-required service while the lower-priority traffic starves at high load. Thus, the SPQ mechanism is not capable to provide really fair scheduling to different types of traffic in EPONs.

In the TSQ mechanism, multiple priority queues and a first-in-first-out (FIFO) queue are deployed in the two queuing stages, respectively. Packets are sequenced in the first stage by priority queues when arriving at the ONU. When it comes to transmission, the ONU advances packets from the priority queues to the FIFO queue before transmitting them over the upstream link. Additionally, higher-priority packets cannot replace lower-priority packets. Although TSQ can improve the performance of the lower-priority traffic, the performance of the higher-priority traffic is sacrificed without the guarantee of the service requirements.

A priority-based scheduling algorithm is proposed for intra-ONU scheduling in [6]. In this algorithm, the ONU sends a Report-message to the OLT notifying the queue information at time t_1, then OLT replies with a Gate-message to let the ONU transmit packets. When the ONU is polled by the OLT, it first transmits packets arriving before t_1 based on their priorities. If all packets arriving before t_1 are served, and the current transmission window can carry more traffic, then packets arriving after t_1 can be transmitted according to their priorities. This mechanism is actually a gated strict priority scheduling method. It can improve the fairness among all traffic classes by allowing them access to the channel as reported to the OLT. While it allows higher-priority packets to replace lower-priority packets if the buffer is full, this will result in starvation of the lower-priority traffic at heavy load.

All the above mechanisms have not taken into account the requirements of various traffic streams. So they cannot obtain the objective of fair scheduling. In order to achieve the fair scheduling in EPONs, we propose the UFQ scheme for intra-ONU scheduling in this paper. Incorporating the traffic's requirements into the scheduling design, UFQ can provide the remaining bandwidth to the best-effort traffic and guarantee the requirements of different types of QoS traffic. The UFQ scheme is introduced in detail in section 'Intra-ONU scheduling scheme'.

Hierarchical scheduling

In EPONs, multiple ONUs should share the bandwidth to transmit packets over the upstream access network. At the same time, different traffic streams in one ONU will also share the bandwidth allocated to the ONU for transmission. Here a hierarchical scheduling architecture is necessary in EPONs, as shown in Fig. 1. It consists of inter-ONU scheduling and intra-ONU scheduling. It will efficiently assign the upstream bandwidth among multiple ONUs and provide differentiated services to different types of traffic.

The coordination among the multiple ONUs is the inter-ONU scheduling, which is performed by the OLT. As a central controller, the OLT cyclically polls multiple ONUs in an adaptive sequence to control the upstream channel sharing among different ONUs. Contentions between the ONUs can be eliminated by means of the efficient MAC scheme described in section 'inter-ONU scheduling protocol'. The deployed MAC scheme consists of three separate, closely related components: the CAC mechanism, the EDA algorithm, and the BGP scheduling scheme. The scheme incorporates QoS and SLA into the MAC protocol design. It can guarantee bandwidth for high-demand ONUs and can provide best-effort service to low-demand ONUs.

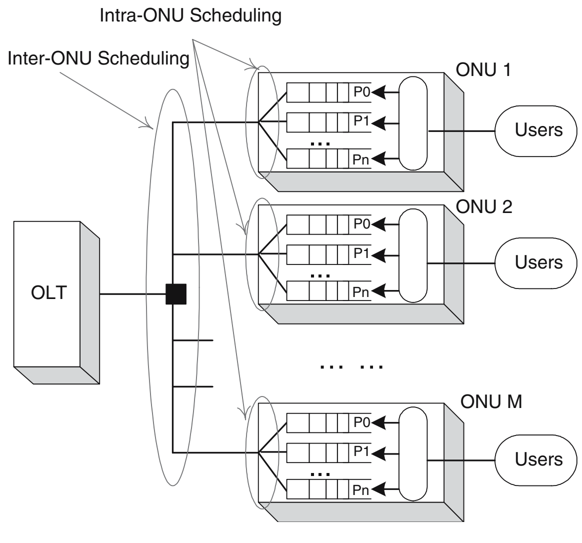


Fig. 1 Hierarchical scheduling in EPONs

Intra-ONU scheduling within the ONU is performed by each ONU. We propose the UFQ scheme for intra-ONU scheduling which will be presented in section 'inter-ONU scheduling protocol'. The ONU classifies, sequences, and transmits different traffic streams in accordance with the UFQ scheme. Differentiated types of traffic in the same ONU will be treated differently and will be transmitted in different precedence $P_0, P_1, \ldots, P_n$, thus supporting DiffServ in the EPON transmission. Moreover, the UFQ scheme can provide bandwidth to best-effort traffic as much as possible without violating the requirements of different QoS traffic streams. Fairness can be achieved among different types of traffic.

In our system, the ONUs are divided into two disjoint groups based on the SLA: bandwidth guaranteed (BG) ONUs and bandwidth non-guaranteed (non-BG) ONUs. The OLT maintains a scheduling table called Entry Table that keeps the sequence of entries being polled. Table entries are similar to time slots in a TDM system, which will be either allocated to BG ONUs or dynamically assigned to non-BG ONUs. The OLT polls ONUs for upstream transmission in the order of the Entry Table according to the inter-ONU scheduling scheme. Hence, multiple ONUs can share the upstream channel without collision. The OLT also maintains a list of non-BG ONUs to determine the polling order of non-BG ONUs. In a BG ONU, the bandwidth guarantee is achieved by allocating one or more entries in a poll cycle. In addition, best effort service is provided to a non-BG ONU by dynamically assigning the remaining entries in the table, and assigning the remaining transmission window in the entry. Each ONU buffers data packets received from the end users until its turn to transmit. When its turn arrives, the ONU will "burst" out packets to the OLT at full channel capacity. Different types of traffic in the ONU are scheduled for transmission according to the intra-ONU scheduling scheme.

Two kinds of control messages are transferred in our hierarchical scheduling: Grant and Reply. Compatible with the MPCP, Grant and Reply messages are generated and delivered by the OLT and ONUs, respectively. In the inter-ONU scheduling, the OLT sends Grant messages to ONUs based on the adaptive order, informing ONUs to transmit the granted amount of packets at the appropriate time. When receiving a Grant message, the ONU reports its buffer occupancy information to the OLT by sending out a Reply message. Then according to the intra-ONU scheduling mechanism, the ONU delivers its data packets of different traffic streams at the prescribed time.

Inter-ONU scheduling protocol

In the inter-ONU scheduling among multiple ONUs, we deploy the efficient MAC protocol proposed in [8], which contains three parts operating autonomously but closely related to each other. The parameter-based CAC mechanism processes the customers' requirements expressed in SLA parameters, decides which group each ONU belongs to (BG or non-BG group), and determines how many entries each BG ONU gets allocated. Based on the results of CAC, the EDA algorithm generates the Entry Table and the non-BG ONU list to set the polling sequence. Then by the BGP scheme, the OLT polls ONUs one after another based on the results of EDA, inviting ONUs to transmit data over the channel. The entire proposed scheme is implemented at the OLT.

The CAC mechanism will be described in detail because it takes into account the end users' requirements, which is different from the one in [7].

Parameter-based cac mechanism

The CAC mechanism decides which transmission requests could be admitted for transmission and what kind of service would be provided to the transmission. Its decision is based on whether the QoS requirements of all requests can be met under the limited network resources. The major advantage of our CAC mechanism is that it will accept all requests with certain QoS requirements at all circumstance. If the requirements of the transmission cannot be satisfied, the CAC scheme will suggest to provide downgraded services.

During the initialization of the EPON scheme, all end users request the QoS requirements for transmission and negotiate the SLA contracts with the service provider. The QoS requirement is expressed as parameter pair $\langle B, D, P \rangle$, where B specifies the minimum peak bandwidth the user requests, D indicates the maximum waiting delay the user can tolerate, and P is the maximum bandwidth the user is able to pay. The SLA contracts can come to terms after calculation, comparison, and allocation. Then the CAC mechanism decides the members of the BG and the non-BG ONU groups, and determines how many bandwidth units/entries each BG ONU can be allocated according to the SLA contracts. The operation flowchart is shown in Fig. 2, where the calculation formulas are given in [7]. In each ONU, the payment of end users should be proportional to their QoS requirements.

During the operation of the system, there may be a new user joining the existing ONU. Another case is that some ONUs may be inactive at the initialization and request for network transmission service during the operation period. The CAC mechanism processes these issues using the operation similar to that during the initialization period.

Evenly distributed algorithm

After performing the CAC mechanism, the members of each ONU group (BG or non-BG group) and the number of members in each ONU group can be determined. Then the OLT employs the Evenly distributed Algorithm (EDA) algorithm to prepare the Entry Table and the non-BG ONU list that will be used in the BGP scheme.

Since one BG ONU may be allocated more bandwidth than the bandwidth of one entry, it has to be polled more than once in each polling cycle. The EDA evenly distributes the multiple entries to the same ONU among all entries in the Entry Table, to space out the traffic from the same ONU. So the traffic of this ONU can be evenly distributed over the upstream channel when they are polled based on the Entry Table. It will privilege the BG ONUs with high traffic load since the packets in the buffer can be allowed to transmit after the same intervals. Thus, there will be reduced burst in the access delay. The detailed operation of the EDA algorithm can be found in [8].

Bandwidth guarantee polling scheme

After the Entry Table and the non-BG ONU list have been prepared by EDA, the BGP scheme is invoked to control the entire operation of the inter-ONU scheduling. As being the kernel of the inter-ONU scheduling scheme, BGP is responsible for upstream bandwidth allocation and controls data transmissions from multiple ONUs to the OLT.

Since all entries in the Entry Table are allocated to fixed BG ONUs or dynamically assigned to non-BG ONUs in BGP, the Entry Table together with the non-BG ONU list will determine the scheduling order of ONUs, based on which the OLT will poll ONUs one after another [8]. When the OLT decides to poll the next entry in the Table, it will first locate which ONU is allocated to this entry and then grants a transmission window to this ONU by sending a Grant message. Upon receiving the message, the ONU reports its buffer occupancy status by sending a Reply message to the OLT and transmits data packets up to the duration of the transmission window according to the intra-ONU scheduling scheme described in the next section.

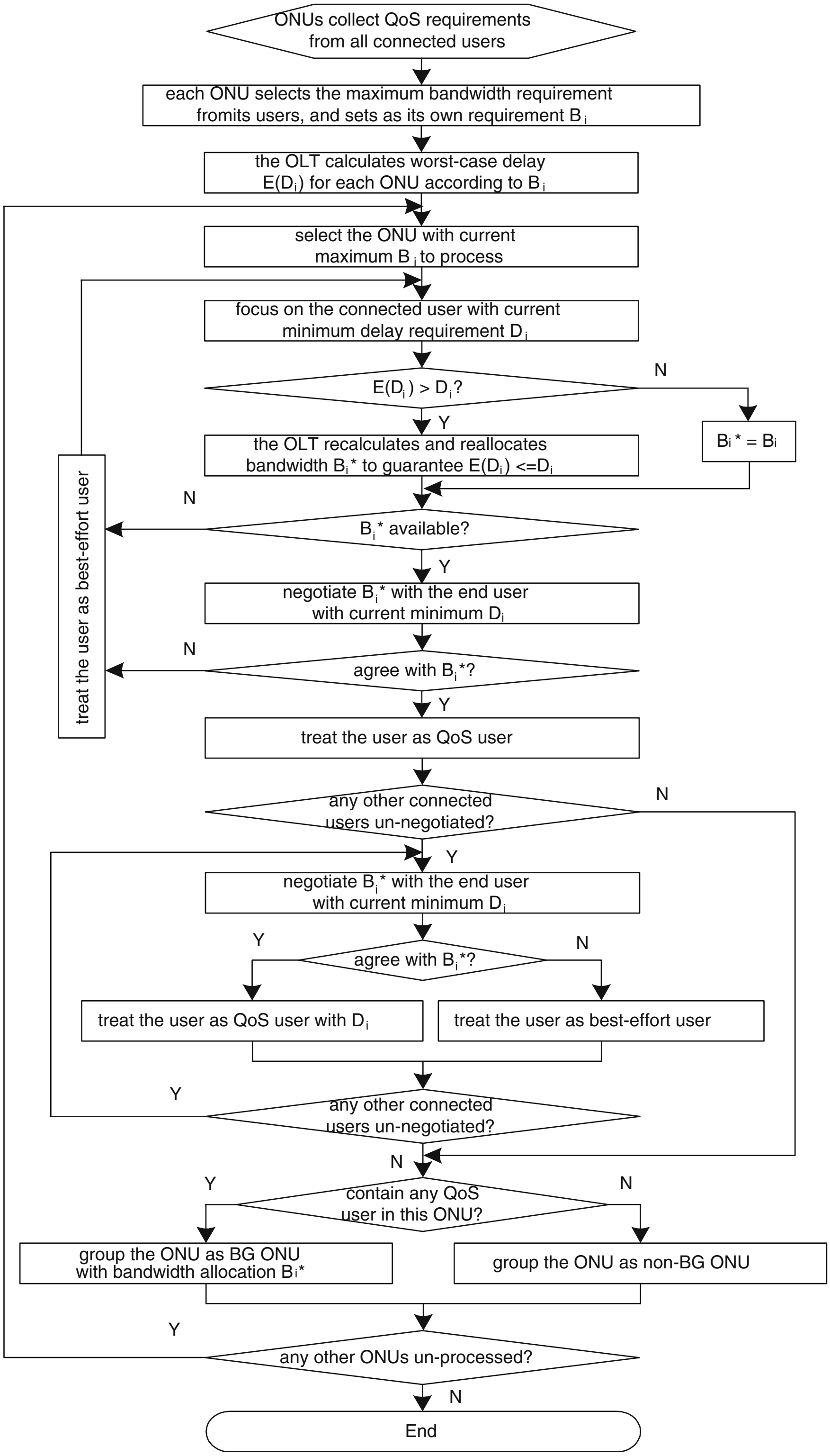


Fig. 2 CAC flowchart during the initialization period

Intra-ONU scheduling scheme

In the hierarchical scheduling, ONUs perform the intra-ONU scheduling scheme to provide differentiated services (Diffserv) for different users. Service requirements, especially the delay bound requirements, are considered in the proposed UFQ scheme in order to achieve the fairness as well as support the differentiated services.

Traffic requirements and classification

According to the IETFs Diffserv Working Group (WG) [9], Internet traffic is classified and forwarded in a Per-Hop Behavior (PHB) according to their service requirements. The Expedited Forwarding (EF) PHB is designed to provide low loss, low delay, low jitter, assured bandwidth, or end-to-end service. Generally, the EF PHB emulates a virtual leased line to support highly reliable voice or video as dedicated circuit services. The Assured forwarding (AF) PHB is a group of PHBs designed to ensure that packets are forwarded with a high probability of delivery, as long as the aggregate traffic in a forwarding class does not exceed the subscribed information rate. The AF PHB group includes four traffic classes. The packets within each AF class can be further marked with one of three possible drop-precedence values. The classification allows the service providers to offer differentiated levels of forwarding assurances for IP packets. The default PHB is specified as the conventional best-effort forwarding behavior. When no other agreements are in place, all packets are assumed to belong to this traffic aggregate.

In this paper, we assume to have two kinds of QoS traffic and a best-effort traffic corresponding to EF, AF, and default PHBs, respectively. The traffic with higher QoS requirements has a strict delay bound, and the traffic with lower requirements has a loose delay bound. The best-effort traffic has no delay bound requirement.

Urgency fair queuing scheme

We propose the UFQ scheme for the intra-ONU scheduling. It can provide differentiated services to different users and also achieve fairness among different types of traffic in the same ONU. By taking into account the traffic's QoS requirements, UFQ can provide better services to the best-effort traffic without violating the service requirements of the QoS traffic streams.

The key point of the UFQ scheme is to assign as much as possible bandwidth to the best-effort traffic, while it still can guarantee the requirements of different QoS traffic streams. To achieve this point, delay bound requirements of the QoS packets are considered in UFQ. We introduce the Urgency Parameter $U_k^j(t)$ to indicate the urgency of packet k belonging to the QoS traffic j to be transmitted in the ONU. It takes into account the packet's delay bound, transmission time and waiting time in the ONU. The Urgency Parameter is used as the sole criterion for QoS packet transmission in the UFQ scheme. Packets with smaller Urgency Parameter will be served earlier than packets with a lager one. $U_k^j(t)$ is expressed as:

$$U_k^j(t) = d_k - v_k(t) - L_k/C,$$

where d_k is the delay bound requirement of packet k, $v_k(t)$ is the packet waiting time in the ONU, L_k is the length of packet k, and C is the link data rate. The waiting time $v_k(t)$ is actually the outcome of the system current time $S(t)$ minus the packet arrival time A_k: $v_k(t) = S(t) - A_k$. Since $v_k(t)$ increases as the time elapses, the value of $U_k^j(t)$ is decreasing with the packet waiting in the buffer.

In the UFQ scheme, packets in different QoS traffic streams are transmitted based on their Urgency Parameters, which can be regarded as the transmission priorities. Since the packet's delay bound, transmission time and waiting time have been mapped into the Urgency Parameter, it can represent the urgency/priority of the QoS packets to be transmitted. The smaller the $U_k^j(t)$ value, the more urgent this packet requires to be sent out. A packet with $U_k^j(t) < 0$ will be dropped because its delay bound is already infringed. Meanwhile, a packet with a large $U_k^j(t)$ can be delayed for transmission, giving way to the best-effort packets to go through the link.

The best-effort packets have no related Urgency Parameters. They are transmitted when all packets in the QoS traffic are deferred for transmission due to the large values of Urgency Parameters. By using some bandwidth that the QoS traffic cannot consume, the best-effort traffic will get better performance than in other mechanisms. In this way, the UFQ scheme can provide the fairness among different traffic streams in the same ONU, by offering better performance to the best-effort traffic while still ensuring the service requirements of different types of QoS traffic.

Packet arrival in the UFQ scheme

The ONUs buffer is divided into multiple queues to accommodate different types of traffic, including multiple QoS queues $(Q_1, Q_2, \ldots Q_n)$ and one best-effort queue BE (Fig. 3). According to their QoS requirements and characteristics, packets from different end users are classified to different classes and sequenced into different QoS queues before transmission. Packets without

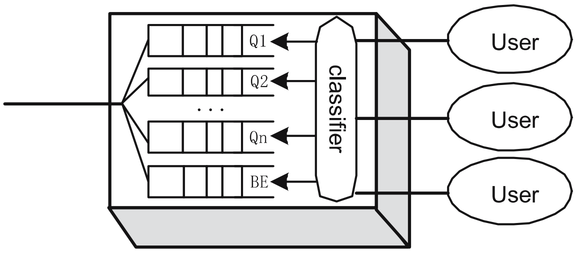


Fig. 3 The ONU structure in the UFQ scheme

any QoS requirement are inserted in the BE queue. There is no packet replacement in UFQ. If the finite buffer is full, the newly arriving packet will be dropped no matter which class it belongs to.

When arriving at the ONU, a new packet k with QoS requirements will be assigned the original value of the Urgency Parameter $U_k(0)$. After being stamped with $U_k(0)$ and the arrival time A_k, packet k is inserted into the relevant QoS queue Q_j according to its original Urgency Parameter value $U_k^j(0)$. Since the arrival time A_k equals to the system current time $S(0)$ when the packet newly arrives at the ONU, the packet waiting time $v_k(0) = 0$. So the original Urgency Parameter value of packet k in queue Q_j is:

$$U_k^j(0) = d_k - L_k/C,$$

$$\forall Q_j \in (Q_1, Q_2, \ldots, Q_n).$$

After comparing with the Urgency Parameter values of the existing packets in queue Q_j, packet k will be inserted into queue Q_j after packets with $U_m^j(t) \leqslant U_k^j(0)$ and before packets with larger $U_m^j(t) > U_k^j(0)$. The urgency value of an existing packet m in queue Q_j can be calculated as follows, whose $U_m^j(0)$ and A_m was stamped when it arrived at the buffer:

$$U_m^j(t) = d_m - v_m(t) - L_m/C = U_m^j(0) + A_m - S(t),$$

$$\forall Q_j \in (Q_1, Q_2, \ldots, Q_n).$$

Newly arriving packets without QoS requirement are simply inserted in the tail of the *BE* queue in the ONU. So packets in the BE queue are sequenced in a FIFO manner. The operations of ONU receiving a packet in UFQ are as follows:

The ONU receives packet k

```
if (the buffer is not full)
    if (packet $k$ has no QoS requirements)
        insert packet $k$ at the tail of the BE queue;
    else
        find the corresponding QoS queue $Q_j$;
        stamp packet $k$ with the arrival time $A_k$ and the original urgency value: $U_k^j(0) = d_k - L_k/C$;
    if (queue $Q_j$ is not empty)
        get the head packet $m = 0$;
        while ($U_m^j(t) < U_k^j(0)$)
            $m = m + 1$;
        insert packet $k$ before packet $m$;
    else
        insert packet $k$ at the tail of QoS queue $Q_j$;
else
    drop packet $k$;
```

Packet transmission in the UFQ scheme

When the ONU is polled by the OLT, it will transmit QoS packets in the increasing order of their Urgency Parameter values $U_k^j(t)$, and serve the best-effort packets during the intermission when all QoS packets are delayed for transmission due to the large values of the Urgency Parameter.

Before transmission, the ONU compares the Urgency Parameters of all packets in the QoS queues and selects the packet with the minimum value. Since packets in each QoS queue are sequenced in increasing order of $U_k(t)$, the ONU only needs to compare $U_k(t)$ of the head packets ($k = 0$) in different QoS queues ($Q_1, Q_2, \ldots Q_n$), instead of all QoS packets in the buffer. Assume that the head packet in QoS queue Q_j is selected with the minimum $U_0^j(t)$ value. This packet is also the one most urgent for transmission among all QoS packets. The Urgency Parameter value of this head packet is:

$$U_0^j(t) = U_0^j(0) + A_0 - S(t).$$

If $U_0^j(t)$ of the selected packet is less than 0, then this packet will be dropped because its delay bound will be violated even though it is transmitted immediately. If this $U_0^j(t)$ is between 0 and the cycle time plus a guard time ($TC_i + G$), then this packet will be sent out by the ONU immediately. If the $U_0^j(t)$ is larger than ($TC_i + G$), this packet and all other packets in QoS queues will be deferred for transmission. The reason is that Urgency Parameters of all QoS packets are large enough, which means their delay bounds are far from being infringed. So all QoS packets are not urgent for transmission and can wait in the buffer for longer time. In this case, the head packet in the best-effort queue will be transmitted.

The guard time G is set to ensure the QoS packets be transmitted before their delay bound violation. It is different from the guard time between the adjacent time slots in the inter-ONU scheduling scheme. G is a system parameter that is related to the system traffic load and traffic requirements. A large value of G can give good protection for the QoS traffic, and provide worse performance to the best-effort traffic, and vice versa. The cycle time TC_i is the time period between the two consecutive times that ONU i is polled. For an EPON system with average scan time of $\overline{t_c}$, the cycle time of the ONU with n bandwidth units/entries can be expressed as follows:

$$TC_i = \overline{t_c}/n = (N * \overline{\tau} + 3P * \overline{\tau} + N * W_{\max})/n,$$

where N is the ONU number in the system, $\overline{\tau}$ the average propagation delay from the ONU to the OLT, $W_{\max}$ the maximum transmission window, and P is the number of entries that can be used to poll a second ONU [8]. The operations of ONU transmitting packets in UFQ are as follows:

```
ONU $i$ transmits the packets
while (the granted transmission size is not used up)
    calculate the urgency values of all head packet ($k = 0$)
     in different QoS queues: $U_0(t) = U_0(0) + A_0 - S(t)$;
    for (all QoS queues)
        find queue $Q_j$ whose head packet has the minimum $U_0^j(0)$;
    if ($U_0^j(0) < 0$)
        drop the head packet in queue $Q_j$;
    if ($0 \leqslant U_0^j(0) < (TC_i + G)$)
        transmit the head packet in queue $Q_j$;
    else
        transmit the head packet in the best-effort queue;
```

In the UFQ scheme, packets from different classes of traffic will be interleaved when being transmitted. Thus, the QoS traffic can give some extra bandwidth to the best-effort traffic and still be provided with necessary QoS services. At the same time, the best-effort traffic can get more remaining bandwidth and obtain better performances than in other schemes. By combining the traffic classification with fair scheduling, UFQ can achieve fairness among different types of traffic in the same ONU.

Simulation experiment

We have conducted extensive simulation experiments to model a tree-based EPON network using OPNET Modular 8.1, in order to evaluate the performance of combined inter-ONU and intra-ONU scheduling schemes.

Experimental parameter

In the simulation, we define three types of traffic: QoS traffic Q_1, Q_2, and best-effort traffic BE, corresponding to the IETF specification.

Since most types of traffic are featured by self-similarity and long-range dependencies (LRD) in communication networks, we use a Pareto model to generate self-similar traffic for the Q_2 and BE classes. The traffic is produced by an ON/OFF source model, and the ON time of the traffic follows the Pareto distribution. Packet sizes are uniformly distributed between 64 and 1,518 bytes. For QoS traffic Q_2, the delay bound requirements are not identical for all packets; instead they are exponentially set with a mean value of 400 ms. For the BE traffic, there is no delay bound requirement. The ONU produces variable rate for the traffic with the increase of the system load.

QoS traffic Q_1 has the highest QoS requirements. It is modeled as an interactive application with high reliability. The traffic's delay bound requirement is strict and identical for all packets (set to 10 ms). Each BG ONU generates this type of traffic with a fixed size of 70 bytes and constant inter-arrival time of 125 μs. So traffic Q_1 has a constant data rate of 4.48 Mb/s.

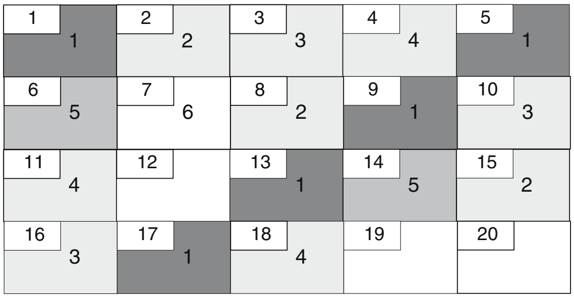
Each BG ONU generates the above three types of traffic independently, and schedules different traffic types using the UFQ scheme. While non-BG ONUs only produce BE traffic. Besides the fixed load of traffic Q_1 generated by BG ONUs, non-BG ONUs produce BE traffic occupying 60% of the remaining system traffic load. The other 40% load is averagely distributed between traffic Q_2 and BE in the BG ONUs.

The simulation system is designed according to a real EPON environment. The tree-based topology is deployed where the system consists of one OLT and 16 ONUs that are connected through a passive splitter. The upstream bandwidth 1 Gb/s is divided into 20 bandwidth units, each with 50 Mb/s (thus there are 20 entries in the Entry Table). Each ONU has a round-trip propagation delay to the OLT, which is uniformly assigned over the interval (50 and 100μ s). The maximum transmission window size $W_{\max}$ is set to 15,000 bytes. The threshold T is $2/3W_{\max}$. Each ONU has a finite buffer (1 Mbytes) in the model, which is shared by the multiple QoS queues and the BE queue.

Scenario design

In this scenario, 16 ONUs are connected to end users with different service requirements, each of which request data transmissions in the initialization period. According to our inter-ONU scheduling scheme, the

Table 1 Entry Table for the simulation modal



1 1	2 2	3 3	4 4	5 1
6 5	7 6	8 2	9 1	10 3
11 4	12	13 1	14 5	15 2
16 3	17 1	18 4	19	20

OLT first performs the parameter-based CAC mechanism to get the members of both ONU groups and the entries allocated to BG ONUs: five entries to ONU 1; three entries to ONU 2–ONU 4; two entries to ONU 5; one entry to ONU 6. All other ONUs are non-BG ONUs. Based on these results, the Entry Table and non-BG ONU List can be obtained by the EDA algorithm. The Entry Table containing 20 entries is shown in Table 1. Since the BG ONUs occupy 17 entries in total, the remaining three entries is completely assigned to non-BG ONUs. The List for non-BG ONUs is sequenced according to the non-BG ONUs' ID in ascending order, starting from ONU 7 and ending at ONU 16.

Then the OLT implements the BGP scheme based on the Entry Table and List, to poll ONUs and let them transmit data over the shared upstream channel. Being polled by the OLT, each ONU will further schedule packets of different traffic Q_1, Q_2, and BE based on the intra-ONU scheduling scheme.

In order to compare the performance of UFQ with the TSQ scheme [5] in the intra-ONU scheduling, we have included the two schemes in the simulation experiments that deployed the same mechanism for the inter-ONU scheduling while UFQ and TSQ for intra-ONU scheduling, respectively. The traffic types, simulation parameters, scenario designs, and delay bound requirements of different QoS traffic types are same in both simulation experiments. The simulation results are presented in the next part.

Experiment results

For each kind of BG ONUs, we collect the average packet delays for the different traffic types, with the system load ranging from 0.1 to 1.0. We can see from the figures that the delay bound requirements for all types of QoS traffic are satisfied well, while the best-effort traffic is provided with good performance. The UFQ scheme can provide better service to best-effort traffic than the TSQ scheme. It also achieves better fairness since it takes into account the QoS requirements of different users.

For BG ONUs with five and three entries, the corresponding traffic delays are almost the same for UFQ and TSQ schemes. This is because they are allocated with enough bandwidth to transmit both the QoS and best-effort traffic. All traffic types in the same group of ONUs experience the similar waiting delay. The delays are very small with values below the delay bound requirements of both QoS traffic types.

Figure 4 compares different traffic average delays for BG ONUs with two entries in UFQ and TSQ schemes. In UFQ, delays for traffic Q_1 and BE are very small and almost unchanged all the time. The delay for traffic Q_2 is small and unchanging at light load. The curves grow up rapidly from the load 0.6, and get to a balanced level (below the mean delay bound 400 ms) after the load of 0.8. In TSQ, although the delay of traffic Q_2 is lower than that in UFQ, delays of traffic Q_1 and BE are much larger than those in UFQ. With the efficiency of the UFQ scheme, the best-effort traffic can get much more bandwidth as well as better performance than in TSQ. At the same time, the two types of QoS traffic in UFQ are provided with the guaranteed services according to their requirements.

Figure 5 shows the average delays of BG ONUs versus network load with one entry in the UFQ and TSQ schemes. In UFQ, delays for both QoS traffic types are less than their delay bounds. Although the delay value for traffic Q_2 is higher than that in TSQ, the best-effort traffic in UFQ experiences lower delay than in TSQ. The UFQ scheme can allocate as much as possible bandwidth to the best-effort traffic and ensure the requirements of the QoS traffic simultaneously.

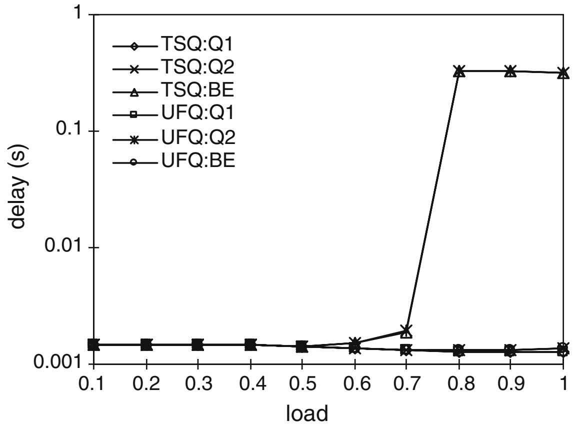


Fig. 4 Average delays of BG ONUs with two entries

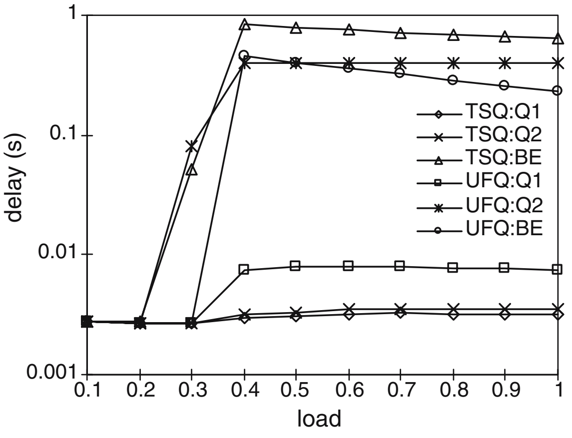


Fig. 5 Average delays of BG ONUs with one entry

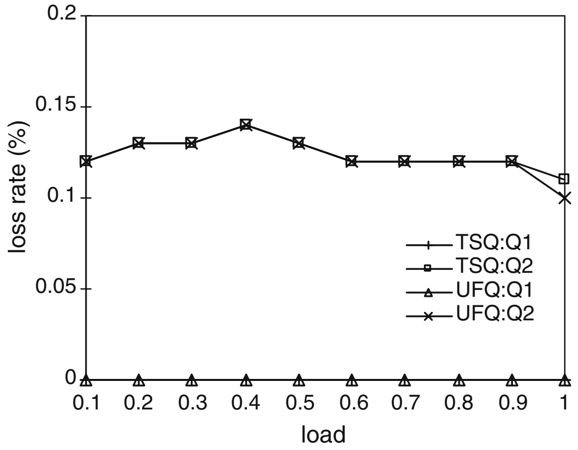


Fig. 6 Loss rate 1 of BG ONUs with five entries

The simulation results suggest that, the UFQ scheme can obviously improve the delay performance of the best-effort traffic, without violating the delay bound requirements of different types of QoS traffic.

In order to prove that the better delay performance in UFQ have not weakened the loss rate performance by dropping more packets, we collect the loss rates for different ONUs' traffic in UFQ and TSQ, respectively, for comparison. The packet with QoS requirements will be dropped if its packet delay bound is violated or the finite buffer is full. So the integrated loss rate of the QoS traffic also consists of two parts: the loss rate due to the violation of the delay bound (we call it loss rate 1 hereafter) and the loss rate due to the fullness of the buffer (we call it loss rate 2 hereafter).

For BG ONUs with five and three entries, loss rates 2 are zero with both UFQ and TSQ schemes because they are allocated enough bandwidth. So loss rates 1 are actually the integrated loss rates of ONUs as shown in Figs. 6 and 7. The corresponding curves in UFQ are almost overlapping with those in TSQ with the same drop rates. For these two kinds of BG ONUs, the drop rates for traffic Q_1 are zero all the time. At some loads, the loss rates for traffic Q_2 are even lower in UFQ than those in TSQ. The loss rate performance has not been impaired in the UFQ scheme.

Figures 8 and 9 compare loss rates 1 and the integrated loss rates for BG ONUs with two entries in the UFQ and TSQ schemes, respectively. Considering the data drop due to the buffer saturation, the loss rates in Fig. 9 are much higher than those in Fig. 8. From Fig. 8, the loss rates of traffic Q_1 with both the UFQ and the TSQ schemes are always zero. Traffic Q_2 with UFQ experiences very low loss rate at all times, thereby dropping fewer packets than in TSQ beyond the load 0.7. In Fig. 9, all the three types of traffic experience very low drop rate below the load 0.7. Then, the curves climb up gradually, with traffic Q_1 slower than traffic Q_2 and BE. The corresponding loss rates in UFQ are a little higher than those in TSQ because of the higher data drop due to the fullness of the buffers. It is proved again that, the improvements of delay performance in UFQ have not aggravated the loss rates for different traffic types.

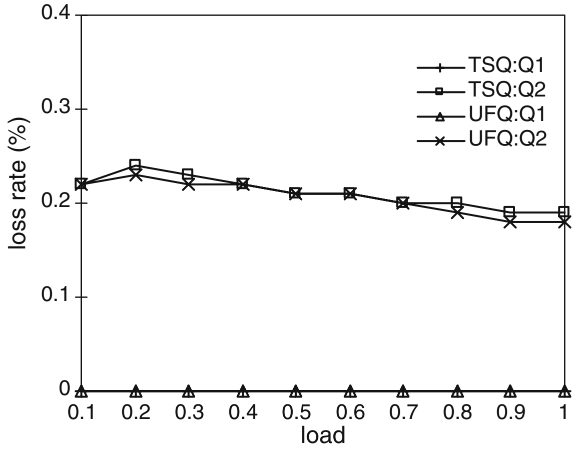


Fig. 7 Loss rate 1 of BG ONUs with three entries

Figures 10 and 11 show different traffic loss rates 1 and integrated loss rates for BG ONUs with only one entry in UFQ versus in TSQ, respectively. Both types of QoS traffic have lower loss rates 1 in UFQ than in TSQ (Fig. 10). For traffic Q_1 and Q_2 with TSQ, more and more packets are queued in the buffer waiting for the service with increasing system load. When the ONUs buffer tends to saturation, more and more packets are dropped before transmission due to the delay bound violation, instead of being discarded due to the fullness of the buffer. When the buffer is full at the load 0.4, loss rate 1 for both traffic types reach the peak values.

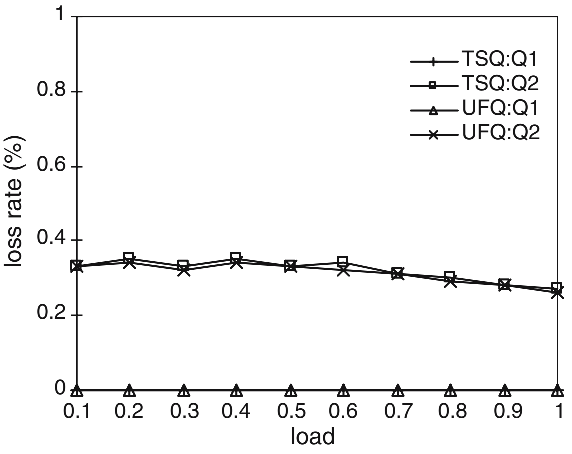


Fig. 8 Loss rate 1 of BG ONUs with two entries

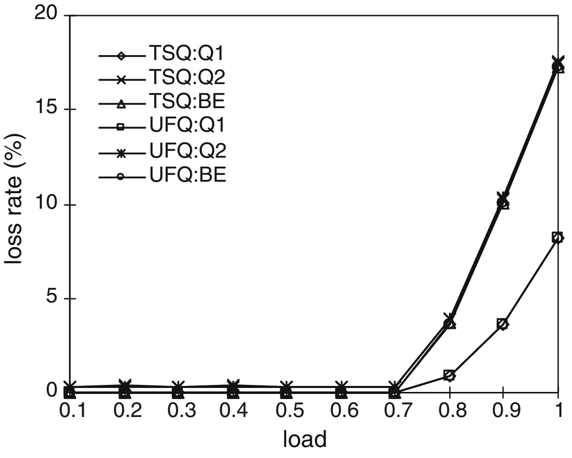


Fig. 9 Integrated loss rate of BG ONUs with two entries

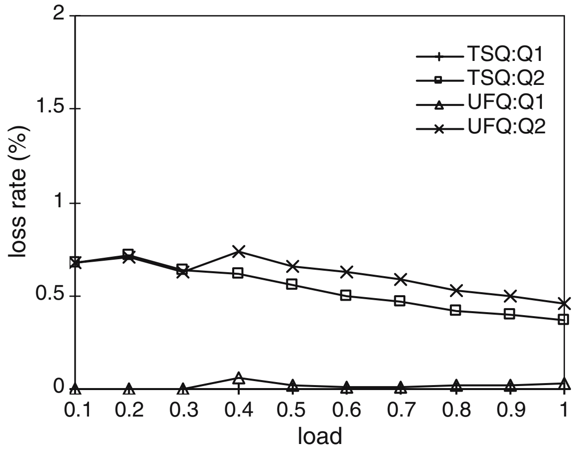


Fig. 10 Loss rate 1 of BG ONUs with one entry

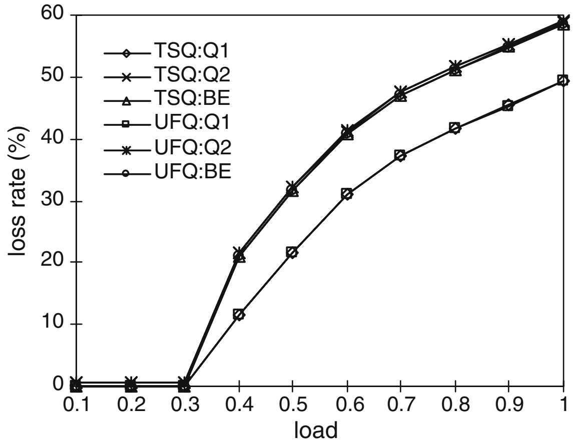


Fig. 11 Integrated loss rate of BG ONUs with one entry

After that load, more packets are discarded due to the fullness of the buffer, leading to fewer packets being dropped due to the violation of the delay bounds. So the loss rates 1 decrease after the saturation load 0.4. For the integrated loss rates in Fig. 11, all the three types of traffic drop a very small amount of packets below the load 0.3. Then the curves climb up gradually slower with traffic Q_1 than the other two types of traffic. The corresponding curves in UFQ are almost overlapping with those in TSQ with the same drop rates. We can see from the figures that, the loss rates in UFQ are not impaired because of the improvement in delay performance.

The simulation results show that, in the UFQ scheme, both types of QoS traffic in the BG ONUs satisfy the bounded delay, and the best-effort traffic is provided with fairly good performance. The QoS requirements are considered to well support DiffServ and fair scheduling in UFQ. Whereas the bandwidth in the TSQ scheme is not allocated as fairly as in UFQ. The QoS traffic streams are provided with much more bandwidth than they need, while best-effort traffic can only get very poor service. The UFQ scheme can achieve better fairness among different traffic types than TSQ while guaranteeing the performance of QoS traffic as well. Moreover, the improvements of the delay performance in UFQ have not weakened the performance of the different traffic loss rates.

Conclusion

In this paper, we have proposed a new scheme, UFQ, for intra-ONU scheduling in EPONs to support differentiated services. Our scheme is designed to achieve fairness among different traffic streams in the same ONU. In the UFQ scheme, packets are scheduled based on the urgency regarding to the delay bound requirements. QoS packets can give way to the best-effort packets for transmission if it is not so urgent for transmission (far earlier than its delay bound expiry). Thus, QoS traffic will give some extra bandwidth to the best-effort traffic and still obtain the necessary QoS service. The simulation results have proved that UFQ is effective to improve the performance of the best-effort traffic and is also efficient to meet the requirements of different QoS traffic streams. The UFQ scheme can achieve better fairness than TSQ in bandwidth sharing among different users.

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