

Fair and Efficient Scheduling Algorithm for EPON

Man-Soo Han

Dept. of Information and Communications, Mokpo National Univ., Korea

mshan@mokpo.ac.kr

Abstract—This paper proposes a new scheduling method to improve fair sharing between service classes and the service fairness among optical network units (ONUs). The proposed method uses a credit pool for each ONU and for each service class. For the service fairness between ONUs, the credit pool of a service class can be negative amount. Also for fair sharing of the upstream channel, the unused credit of a service class is utilized for the negative credit pool of other service classes. Using simulations, we show that the proposed method enhances the service fairness and outperforms the existing methods in mean frame delay.

Index Terms—Dynamic bandwidth allocation; QoS; scheduling; EPON; service fairness

I. INTRODUCTION

Ethernet passive optical network (EPON) is the dominant solution in an access network for the high bandwidth requirements of multimedia applications as it can support data rates of up to 10 Gbps [1]. EPON consists of an optical line terminal (OLT), a passive splitter and multiple optical network units (ONUs). Multimedia applications demand not only high bandwidth but also high quality-of-service (QoS) from EPON. To provide QoS, the Ethernet standard IEEE802.1D classifies input traffic into several class-of-service (CoS) groups. Ethernet manages priorities, queue mappings, and queue service disciplines for multiple CoSs.

A number of DBA algorithms have been developed to provide QoS. Excellent surveys for up-to-date DBA algorithms with multiple CoSs can be found in [3]–[5]. In most algorithms, the OLT collects information from all ONUs before scheduling [2], [11]–[13]. Since the OLT knows the information of all ONUs at the scheduling moment, these algorithms provide service fairness and can iterate scheduling to obtain the high DBA efficiency. However, to collect the information of all ONUs, the upstream channel has to be idle for a while. The idle time consists of the scheduling time, a message processing time at an ONU and a round trip time (RTT) between the OLT and an ONU. In the worst case, the RTT can be 0.2 ms with 20-km span in the current EPON standard [6].

In an EPON system, a transmission cycle starts at the beginning of transmission of a specific ONU and ends at the beginning of next transmission of the same ONU. Within a transmission cycle, each ONU has only one transmission time slot. In many articles, the typical maximum value for the transmission cycle time ranges from 0.75 ms to 2 ms [3]–[6], [8]–[10]. If the OLT collects information from all ONUs before scheduling, the transmission cycle time includes the upstream channel idle time. In the worst case, more than 10% (20%) of the upstream channel bandwidth is wasted when the

maximum transmission cycle time is 2 ms (1 ms) and the RTT is 0.2 ms.

In a few algorithms such as fast class-of-service oriented packet scheduling (FCOPS) and efficient class-of-service oriented packet scheduling (ECOPS), the OLT produces a scheduling result immediately after receiving information from a single ONU to eliminate the idle time [7], [14]. However, these algorithms provide poor service fairness and suffer from low scheduling efficiency since the OLT does not know information of other ONUs at the moment of scheduling and since the OLT cannot repeat scheduling to get high efficiency.

FCOPS is based on class-of-service oriented packet scheduling (COPS) [2]. In COPS, to provide fair sharing of the upstream channel, a credit pool is used for each CoS and each ONU. CoS and ONU credit pools represent the guaranteed bandwidths per a transmission cycle for CoS and ONU, respectively. In COPS, the OLT starts scheduling only after it receives all requests from all ONUs. The OLT grants the largest request of a queue that is less than or equal to the CoS credit and the ONU credit. Each credit is reduced by the grant size. When scheduling is finished, the OLT repeats scheduling with the remaining unused CoS credits to get high scheduling efficiency. Since COPS starts scheduling only after the OLT receives requests from all ONUs, it has the problem of the upstream channel idle time.

FCOPS eliminated the idle time of COPS [7]. To do so, the OLT immediately grants a request if its corresponding CoS credit pool and ONU credit pool are sufficient. But this scheme introduces two problems. The first problem is service unfairness between ONUs [7], [14]. Since the initialization moment of credit pools is fixed at a particular ONU, ONUs have unequal service opportunity [14]. The first ONU in the transmission cycle has the highest opportunity while the last ONU in the transmission cycle gets the lowest opportunity. The second problem is that the unused CoS credit was not fairly utilized. The unused CoS credits were used only for the CoS with the lowest service priority. The unused credit of a CoS has to be used for other CoSs in the order of service priority for fair sharing of the upstream channel among CoSs. In [7], it was shown that FCOPS outperforms COPS.

The service unfairness problem of FCOPS is mitigated in ECOPS [14]. In ECOPS, the initialization moment of credit pools is not fixed but fairly distributed to each ONU. ECOPS introduced a credit initialization (CI) cycle that is longer than a transmission cycle and its starting point is changed in a round robin manner. Every CoS credit pool is initialized at the beginning of the CI cycle. Like FCOPS, ECOPS has the same utilization problem of unused CoS credits. To the best of our knowledge, there is no EPON scheduling method for

multiple CoSs that does not have the idle time, has fairness among ONUs and fairly utilizes unused CoS credits.

In this paper, we propose a new DBA algorithm, called fair and efficient scheduling (FES) algorithm, which does not have the idle time but provides good service fairness among ONUs and fairly utilizes the unused CoS credits. Unlike other methods, the FES algorithm allows a negative value in the CoS credit to eliminate the service unfairness among ONUs. FES grants a request if the corresponding ONU credit is sufficient and the sign of the corresponding CoS credit at the beginning of the transmission cycle is positive. Both credits are decreased by the grant amount.

At the beginning of the transmission cycle, the ONU credit is reset to its maximum value. Also, at the beginning of the transmission cycle, the CoS credit is increased by its maximum value. At the end of the transmission cycle, the unused CoS credits are added to the CoSs with negative credit in the order of service priority. Using simulation, we show that the performance of FES is superior to FCOPS and ECOPS in mean frame delay and service fairness.

The rest of this paper is organized as follows. In section II, we explain the EPON system model and operation. Section III introduces FES algorithm. Section IV shows simulation results. Finally we conclude in section V.

II. SYSTEM MODEL

The EPON system consists of an OLT, a passive splitter and N ONUs. Each ONU has M queues, one for each CoS. An incoming frame from users to ONU i is saved in the queue q_{ij} if the CoS of the frame is j . In the downstream direction, the OLT broadcasts frames through the splitter to all ONUs. Each ONU accepts only frames that have the media access control address that belongs to the ONU. In the upstream direction, the ONUs share the channel bandwidth and only one ONU can transmit frames to the OLT at any time due to the splitter property.

EPON uses the REPORT message to carry up to 20 requests of a particular ONU [1]. Also, EPON uses the GATE message to notify the grant information to each ONU. Every ONU must send a REPORT message at the end of its data transmission to report its queue status to the OLT. Even if an ONU is empty, the REPORT message is sent to the OLT. For each ONU, the OLT assigns a transmission time slot for data as well as for the next REPORT message. Then the OLT delivers the scheduling result to the ONU using a GATE message.

A transmission cycle is shown in Fig. 1. The cycle starts at the beginning of transmission of a specific ONU (ONU 1 in Fig. 1) and ends at the beginning of next transmission of the same ONU. In Fig. 1, G means a GATE message and R means a REPORT message. In this paper, without loss of generality, we assume ONU 1 is the specific ONU in any case. During the cycle time, each ONU has only one transmission slot. A guard time g is followed by the end of each transmission slot. If the OLT sends a GATE message to ONU 1 at time t , the message arrives at ONU 1 at time $T_s = t + \frac{RTT}{2}$ where RTT is the round trip time of ONU 1. Also, the shortest time that the first data bit of ONU 1 can arrive at the OLT is

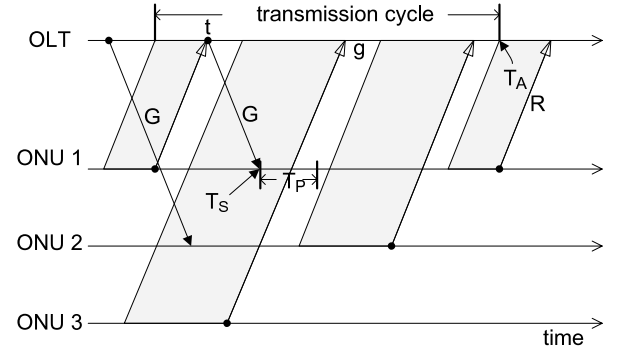


Fig. 1. Transmission cycle

$T_A = t + T_p + RTT$, where T_p is the combined maximum delay of GATE message at the OLT and the minimum processing time at ONU 1 and the standard minimum value of T_p is $16.384 \mu s$ [1].

The OLT has N ONU credit pools and M CoS credit pools. We represent the values of an ONU i credit pool and a CoS j credit pool as u_i and v_j , respectively. The unit of u_i and v_j are a byte. Also, $0 \leq u_i \leq U_i$ and $-B_{max} \leq v_j \leq V_j$, where U_i and V_j are the maximum numbers of bytes that are permitted during a particular transmission cycle by ONU i and CoS j , respectively. The sum of the maximum sizes has to satisfy

$$\sum_{i=1}^N U_i \leq B_{max} \quad \text{and} \quad \sum_{j=1}^M V_j \leq B_{max}. \quad (1)$$

where B_{max} is the maximum number of bytes that ONUs can transmit during a transmission cycle. Note that the CoS credit pool value v_j can be negative in FES unlike in COPS, FCOPS and ECOPS.

Each queue q_{ij} has thresholds for multiple requests. For each threshold, ONU i counts the sum of frame length below the threshold. If a frame is partially below the threshold, ONU i does not count the length of the frame since a frame cannot be fragmented in EPON [6]. The maximum threshold value does not exceed B_{max} while the minimum value has to be greater than the minimum frame size. In this paper, each queue q_{ij} sends K requests, r_{ij}^k , $k = 1, \dots, K$, which are in ascending order.

III. FES ALGORITHM

We will briefly review the FCOPS operation. At the beginning of each transmission cycle, the credit pool of ONU i , u_i , and the credit pool of CoS j , v_j , are initialized to U_i and V_j , respectively. ONU i sends multiple requests of q_{ij} to the OLT. When the OLT receives the requests from ONU i , it immediately grants the largest request that is less than or equal to u_i and v_j starting from CoS 1 to CoS M . When a request is granted then u_i and v_j are immediately decreased by the size of the request. Note that $0 \leq u_i \leq U_i$ and $0 \leq v_j \leq V_j$ and the maximum values satisfy Eq. (1).

In FCOPS, both credit pools are always initialized at the beginning of the transmission cycle, which introduces a service unfairness problem [7], [14]. Without loss of generality,

assume the transmission order in the transmission cycle is ONUs 1, 2, $\dots$, N . Because of the REPORT message, the transmission slot size of an ONU is not zero in any case. In addition, since each ONU has only one transmission slot during a transmission cycle, the transmission order does not change in FCOPS. Thus, the grant possibility of ONU 1's requests is highest whereas that of ONU N 's requests is lowest.

Another flaw of FCOPS pertains to the fact that the unused CoS credit can not be fully utilized. For example, consider a system with $N = 6$, $M = 3$, $U_i = B_{max}/6$, $i = 1, \dots, 6$, and $V_j = B_{max}/3$, $j = 1, 2, 3$. Assume that r_{i1}^K , r_{i2}^K , and r_{i3}^K are $B_{max}/9$, $B_{max}/18$, and 0, respectively, $i = 1, \dots, 6$. Since all requests of CoS 3 are zero, the CoS 3 credit is not used. FCOPS will grant $B_{max}/3$ for CoS 1 and $B_{max}/3$ for CoS 2. That is, the requests of q_{i1} , $i = 1, 2, 3$, are granted and the requests of all q_{i2} are granted. FCOPS requires one more transmission cycle to grant the remainder of CoS 1 requests. In this example, the unused CoS 3 credit was wasted. If CoS 1 could utilize the unused CoS 3 credit, all the CoS 1 requests would be granted in a single transmission cycle.

The service unfairness problem of FCOPS was dealt with in ECOPS [14]. ECOPS distributes the initialization moment of CoS credits to all ONU in a round-robin manner to remove service unfairness. The CoS credits are initialized at the beginning of the CI cycle. The CI cycle length is longer than the transmission cycle length. If the CI cycle length is $N + 1$, it means the CI cycle includes transmission of $N + 1$ ONUs and the first CI cycle consists of transmission of ONUs 1, 2, $\dots$, N , 1, and the second one consists of transmission of ONUs 2, 3, $\dots$, N , 1, 2, and so on. Because of the longer cycle length, the size of V_j is increased compared to FCOPS. If the size of V_j is increased, then the likelihood that a request is rejected due to the lack of CoS credit may be decreased. This will make ECOPS better than FCOPS. However, CoS j traffic can not use more than the credit amount V_j during a CI cycle. For example, even if V_1 is totally unused during a CI cycle, CoS 2 can use only V_2 credits during the CI cycle. Since the unused credit can not be utilized, ECOPS also suffers from performance degradation.

We now describe the operation of FES. At the beginning of each transmission cycle, u_i is initialized to U_i and v_j is increased by V_j . The maximum of v_j is limited to V_j . Let m_j denote whether v_j is positive or not after the increase at the beginning of a transmission cycle. If $v_j > 0$ then $m_j = 1$, otherwise, $m_j = 0$. When the OLT receives the requests from ONU i , it immediately grants the largest request of q_{ij} that is less than or equal to u_i only when $m_j = 1$ starting from CoS 1 to CoS M . When a request is granted then u_i and v_j are immediately decreased by the size of the request.

Since the OLT can grant a request even when the CoS credit of that request is negative, FES can utilize the unused CoS credits. For the above example, the requests of all q_{i1} and q_{i2} , $i = 1, \dots, 6$, are granted in a transmission cycle. At the end of the transmission cycle, we have $v_1 = -B_{max}/3$, $v_2 = 0$, and $v_3 = B_{max}/3$. CoS 1 utilized the unused CoS 3 credit and the utilization amount is $B_{max}/3$. Since the utilization is not related with service fairness between CoSs, v_1 must be

increased by the utilization amount.

The utilization can occur when any CoS credit is negative and unused CoS credits exist at the end of a transmission cycle. However the unused CoS credit is not always utilized. For example, if $r_{i3}^K = B_{max}/9$, $i = 4, 5, 6$, in the above example, CoS 1 did not utilize the unused CoS 3 credit but deprived CoS 3 of the grant opportunity. For service fairness between CoSs, v_1 must not be increased by the unused CoS 3 credit. It is complicated and consumes time to calculate the utilization amount of unused CoS credits. For the sake of fast scheduling, we approximately estimate the utilization amount of unused CoS credits rather than precisely calculate it.

Let c_j be the value of v_j at the beginning of a transmission cycle. A portion of the CoS credit of CoS j can be utilized if any CoS is negative and if c_j is greater than the total request size for CoS j at the end of a transmission cycle. The possible utilization amount is at least $\sum_{j=1}^M e_j S(e_j)$, where $e_j = c_j - \sum_{i=1}^N r_{ij}^K$. In addition, $S(x) = 0$ if $x \leq 0$, and $S(x) = 1$ if $x > 0$. Also, we can estimate the possible utilization amount of CoS credits from the sum of v_j 's. A portion of the CoS credits can be utilized if any CoS credit is negative and if the sum of v_j 's is positive at the end of a transmission cycle. In this case, the possible utilization amount is at least $\sum_{j=1}^M v_j$. Hence, the possible utilization amount of unused CoS credits, TS , is at least $TS = \max(\sum_{j=1}^M v_j, \sum_{j=1}^M e_j S(e_j))$.

At the end of each transmission cycle, the estimated utilization amount is added to the negative CoS credit pools in the order of service priority. In the addition, the maximum of v_j is limited to 0. The estimated utilization amount is decreased by the added amount. Fig. 2 shows the pseudo code of FES where g_{ij} is the grant amount of q_{ij} .

For the above unused CoS credit example, $\sum_{j=1}^M e_j S(e_j) = B_{max}/3$, and $\sum_{j=1}^M v_j = 0$. Hence, we get $TS = B_{max}/3$ and it is added to v_1 , so that $v_1 = 0$. That means all unused credits of CoS 3 is utilized by CoS 1. Now let us assume that $r_{i1}^K = B_{max}/9$, $i = 1, \dots, 5$, $r_{i2}^K = B_{max}/18$, for all i , $r_{i3}^K = B_{max}/9$, $i = 1, 2, 3$, and other requests are zero in the above example. Then we get $v_1 = -2B_{max}/9$, $v_2 = 0$, and $v_3 = B_{max}/3$ before the addition of the utilization amount. Also we have $TS = B_{max}/9$ since $\sum_{j=1}^M e_j S(e_j) = 0$ and $\sum_{j=1}^M v_j = B_{max}/9$. Therefore, $v_1 = -B_{max}/9$ at the end of the transmission cycle. In fact, however, CoS 1 utilized $2B_{max}/9$ of the unused CoS 3 credit. In this case, FES underestimated the utilization amount of unused CoS credits.

IV. PERFORMANCE EVALUATION

We consider a system with 16 ONUs that the distance between the OLT is each ONU is 20 Km. Hence the RTT will be 200 μs for each ONU. The upstream link rate is 1 Gbps whereas the line rate from users to ONU is 100 Mbps. Each queue q_{ij} has a same fixed size, 1 Mbytes. The guard time $g = 1 \mu s$ and the process time $T_p = 16.384 \mu s$. The maximum transmission cycle time is 1 ms. B_{max} is calculated as 121,656 bytes from the maximum cycle time, the guard time and the REPORT message size [6].

We consider three CoSs as in [2], [6], [7], [13]. In this paper, we use a total of 12 requests per an ONU, 4 requests per each

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At the beginning of each transmission cycle {
     $u_i = U_i; \quad i = 1, \dots, N$ 
     $v_j = c_j = \min(v_j + V_j, V_j); \quad j = 1, \dots, M$ 
     $m_j = S(v_j); \quad j = 1, \dots, M$ 
}
For each received REPORT of ONU  $i$  {
    for ( $j = 1; j \leq M; j++$ ){
        if ( $m_j = 1$ ){
             $g_{ij} = \max(r_{ij}^k | r_{ij}^k \leq u_i, k = 1, \dots, K);$ 
            if ( $g_{ij} = \text{NULL}$ )  $g_{ij} = 0;$ 
             $u_i = u_i - g_{ij};$ 
             $v_j = v_j - g_{ij};$ 
        }
    }
}
At the end of each transmission cycle {
     $e_j = c_j - \sum_i r_{ij}^K; \quad j = 1, \dots, M$ 
     $TS = \max(\sum_j v_j, \sum_j e_j S(e_j));$ 
    for ( $j = 1; j \leq M; j++$ ){
        if ( $v_j < 0$  and  $TS > 0$ ){
             $A = TS + v_j;$ 
             $v_j = \min(0, A);$ 
             $TS = \max(0, A);$ 
        }
    }
}

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Fig. 2. Pseudo code of FES

queue q_{ij} . Each queue q_{ij} has 4 request thresholds which are $\frac{U_i}{4}$, $\frac{U_i}{2}$, $\frac{3U_i}{4}$, and U_i . We use the self-similar traffic model of [6] where each ONU is fed by a number of Pareto distributed on-off processes. The shape parameters for the on and off intervals are set to 1.4 and 1.2, respectively. The frame size follows the tri-modal distribution [6]. Three frame sizes are 64, 594, and 1518 bytes and their fractions of a traffic load are 62%, 10% and 28%, respectively [2]. Traffic arrival patterns are the same for each algorithm during the simulations.

For ECOPS, we do not use the surplus grant scheme in which an ONU gets a larger grant than its request when traffic is light and the total sum of grants of an ONU is less than a certain minimum size. The ONU uses the surplus grant to transmit frames without reporting its queue size. Since the scheme is effective only when traffic is light, and since the scheme can be easily used in FCOPS and FES without modification, we remove the scheme for the sake of simplicity.

First we consider a balanced traffic scenario in which all ONUs have identical load and all CoSs have identical loads in an ONU. This scenario was widely used in [6], [12]–[14]. Since all ONUs have identical loads, $U_i = B_{max}/16 = 7603$. Let the input traffic load of an ONU be L , where $0 \leq L \leq 1$. Then the input traffic load of each CoS is $L/3$. Also since

we have 16 ONUs with 100 Mbps maximum user line rate, the required average bandwidth for CoS 1 is $16 \times 100/3 = 533.3$ Mbps. To serve all of CoS 1 traffic, we give 55% of upstream channel resource to CoS 1 since the effective upstream bandwidth is $B_{max}/1\text{ms} = 973.2$ Mbps. Since CoS 3 is best effort traffic, we set $V_3 = 0$ like [2] and [7]. The remainder of the upstream bandwidth, 45%, goes to CoS 2.

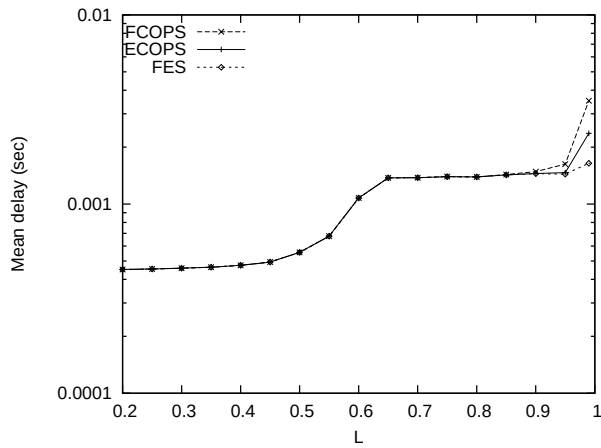
For FCOPS and FES, we have $V_1 = 0.55 \times B_{max} = 66910$ and $V_2 = 54746$. In ECOPS, the length of the CI cycle is 257. Like FCOPS and FES, we give 55% of the upstream channel resource to CoS 1, and the remainder to CoS 2. That is $V_1 = 0.55 \times 257 \times U_i = 1074684$ and $V_2 = 879287$. Increasing L from 20% to 99%, we simulate and measure the performance indexes. For each data point, we perform the simulation until the number of frames transmitted from ONUs exceeds 5×10^8 for each method as in [2].

Figs. 3 (a) and (b) show the mean delay of each method for the first scenario. Mean delay of FES is almost identical to that of FCOPS and ECOPS except mean delay of CoS 1 under heavy traffic. Figs. 4 (a) and (b) indicate the mean delay of ONU 1 and ONU 16 for each method to show the fairness between ONUs. In the transmission cycle, ONU 1 is the first ONU while ONU 16 is the last. In FCOPS, ONU 1 always has the highest service priority while ONU 16 always has the lowest. As one can see from the figures, ONU 16 suffers from service unfairness in FCOPS when the traffic load of an ONU, L , is greater than 90% and 75% for CoSs 1 and 2 traffic, respectively. That service unfairness is mitigated in ECOPS and FES as one can see from Figs. 4 (a) and (b).

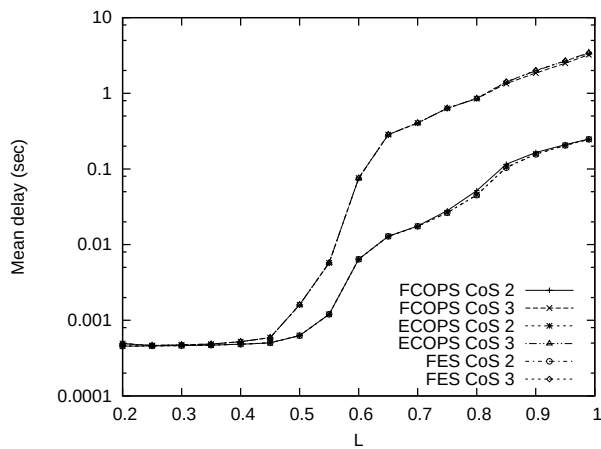
Now we consider the second scenario which has unbalanced CoS traffic. Assume the traffic loads of CoSs 1, 2, and 3 in an ONU are $L/3$, $1/3$, and 0.12 , respectively, where $0 \leq L \leq 1$. Note that CoSs 2 and 3 have a fixed load. Also, as in the first scenario, each ONU has an identical load. We do not give any CoS credit to CoS 3 as in the first scenario. Since the maximum traffic load of CoS 1 is $1/3$, the same values of U_i and V_j of the first scenario are used for each method. Increasing L from 0.05% to 99%, we simulate and measure performance indexes for each method.

Figs. 5 (a) and (b) show the mean delay of each method for the second scenario. In FES, the unused credits are utilized by first CoS 1, then CoS 2, and lastly CoS 3. As a result, FES is the best in mean delay of CoS 2 while the worst in that of CoS 3. FES improves mean delay of CoS 2 up to 80% but aggravates mean delay of CoS 3 up to 53% compared to ECOPS. It is more fair to give the unused credits to CoS with the higher service priority. In this sense, FES provides the best service fairness among CoSs.

FCOPS appears to be worse than FES but better than ECOPS in terms of the mean delay of CoS 2 in Fig. 5 (b). However, Fig. 6 (b) reveals that service unfairness between ONUs is very severe in CoS 2 traffic of FCOPS. Since the mean frame delay is measured only for the frames arriving at the OLT, the mean delay can be distorted by an unfair scheduling algorithm. For instance, if the OLT never serves some of the queues, the mean frame delay would be better than the case where the OLT serves all of them. From Fig. 6 (b), we can see that ONU 16 is less frequently served

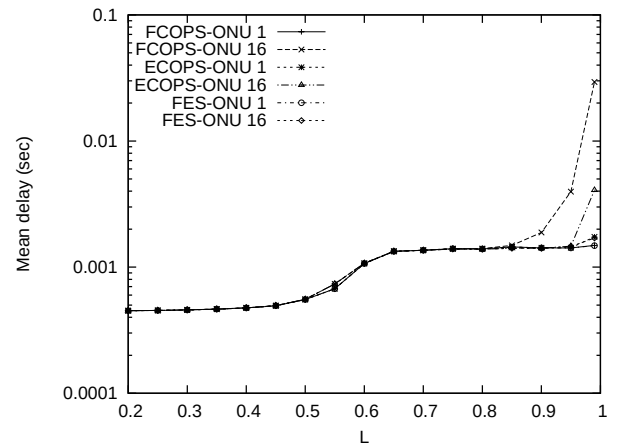


(a) CoS 1

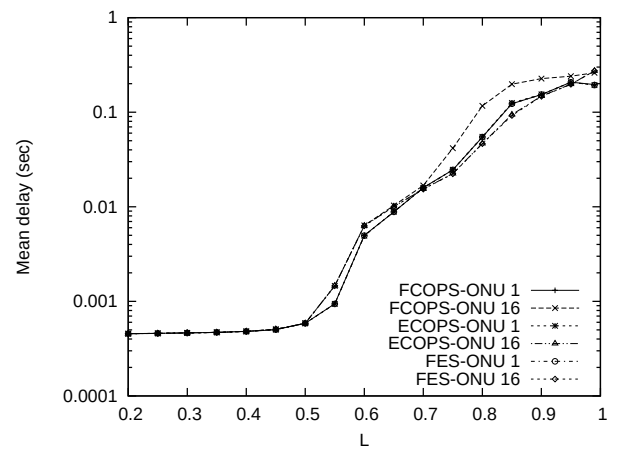


(b) CoSs 2 and 3

Fig. 3. Mean frame delay



(a) CoS 1



(b) CoS 2

Fig. 4. Mean frame delay of ONU 1 and ONU 16

than ONU 1 in FCOPS. As a result, FCOPS has the worst frame loss rate for CoS 2 as in Fig. 7. The frames used in measuring the mean delay mostly come from ONUs having a higher service opportunity in FCOPS. The service unfairness makes the mean frame delay of FCOPS appear better than that of ECOPS which provides a good service fairness between ONUs.

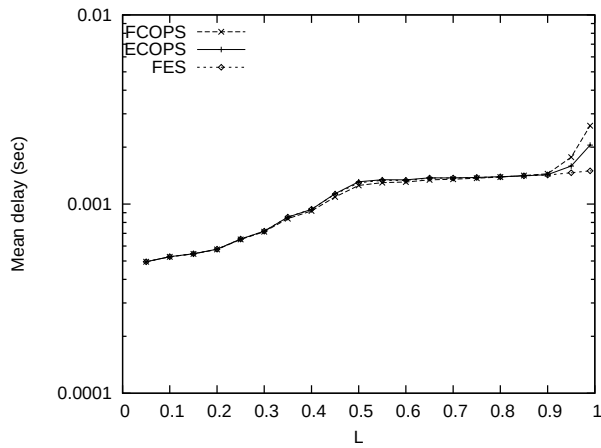
V. CONCLUSIONS

In this paper, we introduced a new scheduling algorithm called FES that resolves the service unfairness problem of FCOPS and utilizes the unused CoS credits. Unlike other existing methods, FES allows a negative value in the CoS credit in order to eliminate the service unfairness between ONUs. FES grants a request if the size of the corresponding ONU credit is greater than or equal to the request size and the sign of the corresponding CoS credit at the beginning of a transmission cycle was positive. For the sake of fast scheduling, FES approximately estimates the possible utilization amount of unused CoS credits. The utilization amount is added to the negative CoS credit pools in the order of service priority at the end of a transmission cycle. This utilization mechanism provides fair sharing of the upstream channel among CoSs.

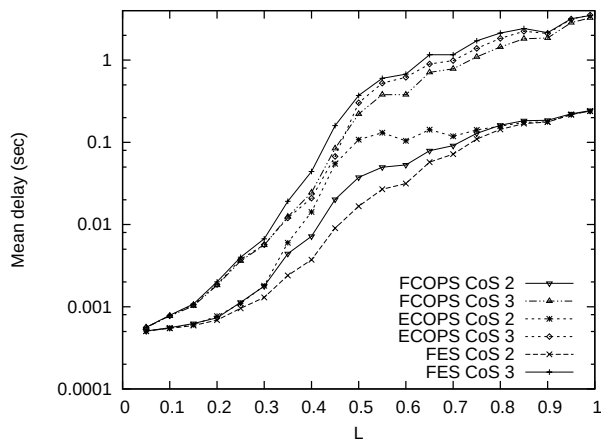
Using simulations, we have shown that FES is superior to both FCOPS and ECOPS in both mean frame delay and service fairness.

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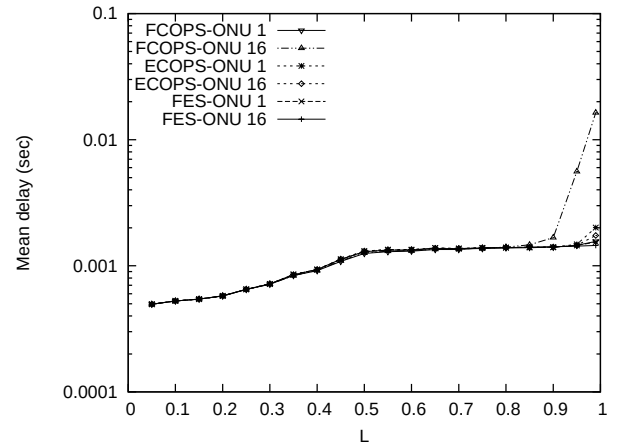
(a) CoS 1



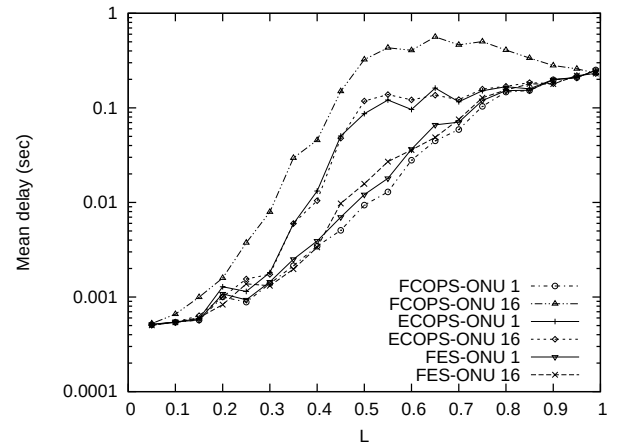
(b) CoSs 2 and 3

Fig. 5. Mean frame delay

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(a) CoS 1



(b) CoS 2

Fig. 6. Mean frame delay of ONU 1 and ONU 16

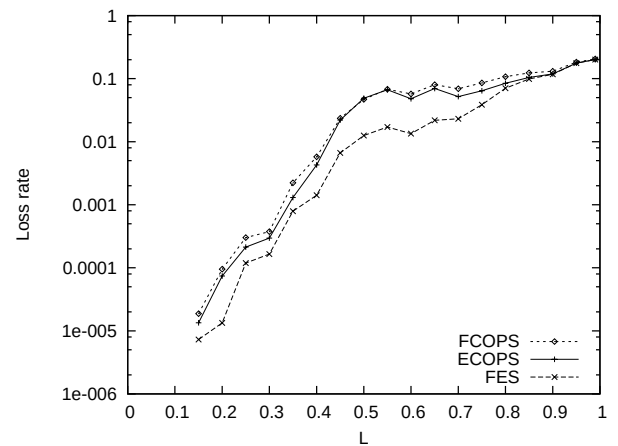


Fig. 7. Frame loss rate of CoS 2