

# Design and evaluation of scheduling algorithms for TDM/WDM PON based on RSOA

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**Abstract** This paper presents a scalable and cost-effective hybrid time division multiplexing (TDM)/wavelength division multiplexing (WDM) passive optical network (PON), in which reflective semiconductor optical amplifiers (RSOAs) are used as optical network units (ONUs) and a shared tunable laser and photoreceiver stack locate at the optical line terminal (OLT). Especially, tunable transmitters are not only shared by all ONUs, but also used for both upstream and downstream transmissions. To solve resource contention problem and provide efficient bidirectional communications between the OLT and the ONUs, two novel algorithms are proposed to manipulate the wavelength accessibility and the burst scheduling. The performance of both algorithms in terms of the average packet end-to-end delay and throughput were simulated and evaluated.

**Keywords** passive optical network (PON), wavelength division multiplexing (WDM), scheduling algorithm, simulation

## 1 Introduction

Nowadays, commercially available passive optical networks (PONs), such as Ethernet passive optical network (EPON) [1] and gigabit PON [2], employ time division multiplexing (TDM) technology to share a single wavelength channel among the optical network units (ONUs). This kind of TDM-PON offers the advantages of low per-subscriber cost, passive realization of remote nodes (RNs), and high reliability, but it inevitably sacrifices per-subscriber bandwidth and has some limitations in terms

of scalability and user privacy. On the other hand, wavelength division multiplexing (WDM) PONs can increase the network capacity and security by creating really point-to-point links between the OLT and ONUs [3]. However, expensive costs, especially of ONUs operating at different wavelengths, prevent it from large-scale application. Moreover, channel sharing is not permitted in a traditional WDM-PON, in which a fixed wavelength is dedicated to an ONU. Besides, the bandwidth demands of the users linked to the same ONU are still under the expected values that a dedicated wavelength can provide.

Therefore, hybrid WDM and TDM technology in a PON architecture is a compromise solution guaranteeing cost effectiveness, full resource utilization and flexible upgrade from TDM to WDM. Here, we present a hybrid WDM/TDM PON architecture based on reflective ONUs, in which a shared tunable laser and photoreceiver stack are at the OLT. To manage the shared resources and offer flexible bandwidth allocation, two novel scheduling algorithms were designed and evaluated by simulations.

## 2 Network architecture

The network architecture is based on a tree topology using  $1 \times N$  arrayed waveguide gratings (AWGs) located in the remote node, as illustrated in Fig. 1. The A WG routes  $N$  wavelengths from the OLT to each outside port, which is directly connected to an ONU, allowing a secure transmission.

At OLT, a tunable shared laser diode (TLD) stack is used to provide data transmission capabilities for both upstream and downstream traffic, and shared by all ONUs. Each TLD can switch to  $N$  wavelengths in order to reach all ONUs it serves. However, two or more TLDs do not tune the same wavelength simultaneously, because this would

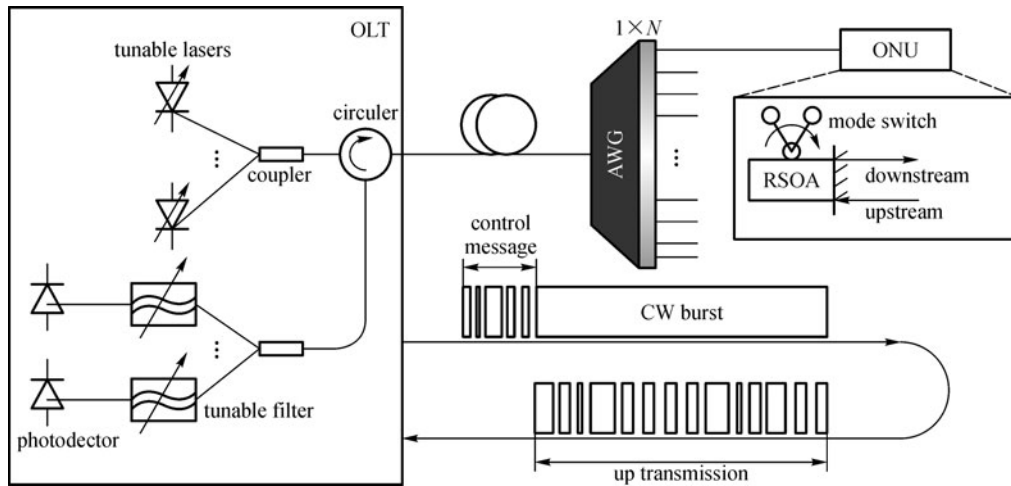


Fig. 1 Network architecture

cause collisions between the optical signals. With TLD working at 1 Gbps, laser tuning times of between 1 and 10  $\mu\text{s}$  would be enough to guarantee correct performance. To offer good performance, tunable lasers with capabilities in the range of hundreds of nanoseconds are required, which have already been reported [4]. The tunable photodetector (TPD) stack provides the OLT reception requirements. Before each photodetector, a tunable filter needs to be added and controlled by the scheduler to select the proper data wavelength for the authorized up-transmitting ONU. The tuning speed has to be less than 1  $\mu\text{s}$  to minimize the transmission overhead. Nowadays, liquid crystal Fabry-Pérot filter and electro-optic tunable filter are candidates to satisfy these capabilities [5]. TLDs and TPDs are coupled together respectively, and then separated from each other by the circulator.

As far as the ONU is concerned, it would be cost prohibitive to use expensive wavelength tunable optical elements, and also impractical for each customer ONU to be built with one or more fixed single wavelength laser. Here, the “colorless” ONU is realized by the use of reflective semiconductor optical amplifiers (RSOAs) [6], which is wavelength seeded by an optical carrier sent from OLT. In such a way, a laser source is avoided at the ONU and there is no problem of cumbersome provisioning and wavelength stabilization. In addition, an RSOA is much cheaper than a tunable LD and is expected to have similar costs to a fixed wavelength LD whose use needs a stock. RSOA is wavelength independent and has two modes of operation: detection and remote modulation mode for up-transmission, which are switched on time basis. The ONU generally works on detection mode and waits for the reception of the downstream traffic; the ONU switches its mode once the up-transmission signaling has been received, and then modulates the upstream traffic onto the following continuous wave (CW) bursts which is sent

by OLT. This configuration results in a half duplex communication between each ONU and the OLT.

The number of TPDs ( $M$ ) can be less than the number of TLDs ( $L$ ) due to the fact that the TLDs are shared by both upstream and downstream traffic while the TPDs are not. In addition,  $L$  should be smaller than the number of ONUs ( $N$ ) connected to the network for cost-sharing purposes. When there is a need to increase the bandwidth per ONU, more TLDs and TPDs can be added at the OLT which is completely transparent from the users’ side.

### 3 Scheduling algorithm

To avoid resource contention and provide efficient bidirectional transmissions between OLT and ONUs, the scheduling algorithms in the media access control (MAC) protocol should be carefully designed. Like the EPON system, OLT needs to poll the ONUs to check the amount of upstream traffic stored inside them. However, the difference is that OLT needs to send corresponding CW bursts to ONUs after granting them upstream transmission. Because the OLT has information about all the data and time references sent to all ONUs, there is no need to synchronize upstream transmission at the ONU level.

Our MAC protocol adopts in-band signaling and the control frame is presented in Fig. 2. The “flags” field is used to indicate frame type. If the value of “flags” field equals to 0, it represents a report message sending to the OLT, and “gate/report” field conveys the required bandwidth. If the value equals to 1, it represents a grant message sending to the ONU, and “gate/report” field represents the total length of the following CW bursts, which corresponds to that of all upstream frames. The frame ends with an 8-bit short frame check sequence for

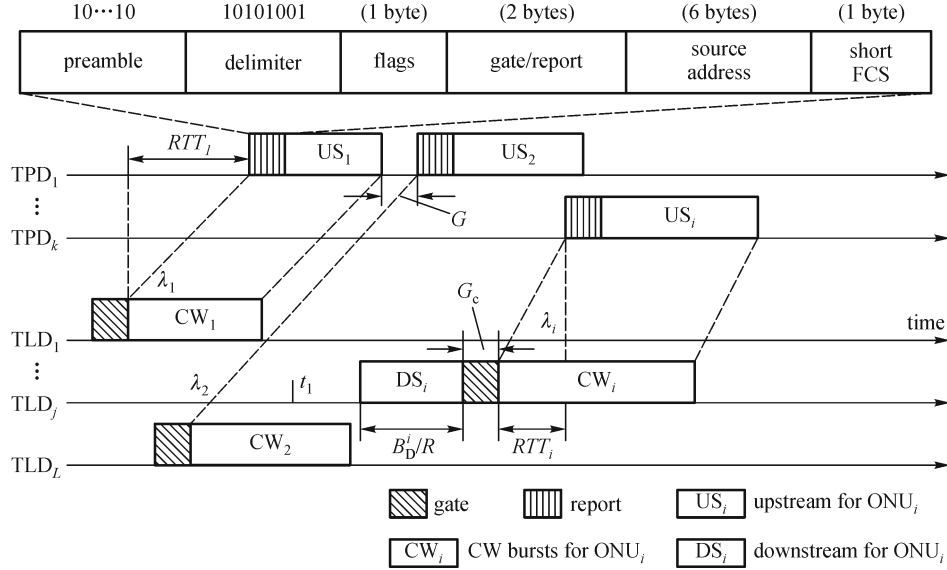


Fig. 2 Example of EATS scheduling algorithm

error detection. ONUs' MAC address is also included to identify itself.

Here, earliest available time scheduling (EATS) is adopted as the base resource allocation mechanism. EATS mechanism attempts to schedule the transmission or reception of packets at the earliest possible time, by selecting a TLD or TPD that is available the soonest. Some global variables that relate to the algorithms should be maintained at OLT:  $Q[i]$  ( $i = 1, 2, \dots, N$ ) represents the downstream traffic queues for each ONU;  $CAT[i]$  ( $i = 1, 2, \dots, N$ ) denotes the wavelength  $\lambda_i$  available time;  $TAT[j]$  ( $j = 1, 2, \dots, L$ ) denotes the transmitter available time;

$$t = \begin{cases} \max \{TAT[j] + G, CAT[i] + G\}, & \text{if } B_U^i = 0, \\ \max \{RAT[k] + G - RTT[i] - (B_D^i/R) - G_c, TAT[j] + G, CAT[j] + G\}, & \text{if } B_U^i \neq 0, \end{cases} \quad (1)$$

where  $G$  is the guard band between consecutive scheduling for different ONUs;  $G_c$  is the transmission time of the control message;  $R$  is the line rate (bps). Then, if there is upstream traffic transmission, OLT schedules the reception of the corresponding upstream frames at  $t + G_c + (B_D^i/R) + RTT[i]$  with the  $k$ th receiver. Finally, OLT updates the related status variables. If there is no upstream transmission,  $TAT[j]$  and  $CAT[i]$  should be updated as  $TAT[j] = CAT[i] = t + (B_D^i/R)$ ; otherwise, they are all renewed as  $t + G_c + (B_D^i + B_U^i)/R$ .

Accord to different polling mode, we propose two algorithms that are all based on the EATS mechanism. One is EATS for single (EATSS) ONU algorithm and the other is EATS for All (EATSA) ONUs algorithm. In the EATSS algorithm, a given ONU is scheduled for upstream transmission as soon as the OLT receives the report message. Furthermore, the report message is transmitted

$RAT[k]$  ( $k = 1, 2, \dots, M$ ) denotes the receiver  $k$  available time;  $RTT[i]$  represents the round trip time between the OLT and the  $i$ th ONU.

Figure 2 also illustrates the process of the EATS algorithm. At  $t_1$ , a report from ONU $_i$  arrives at OLT, and OLT decides the allocated bandwidth  $B_D^i$  (bits) for downstream traffic and  $B_U^i$  for upstream traffic. First, the scheduler selects the earliest available transceiver, and finds that the  $j$ th TLD and the  $k$ th TPD are available now. Then, it schedules the OLT to start transmission with the  $j$ th TLD at time  $t$ , which is as follows:

along with the data in the up window. The dynamic bandwidth allocation (DBA) calculation is done immediately at the arrival of each report message. EATSS is similar to interleaved polling with adaptive cycle time (IPACT) algorithm [7], but the biggest difference is that OLT not only grants for upstream traffic but also for downstream traffic at the same time. The grant strategy for ONU $_i$  can be expressed as follows:

$$B_U^i = \begin{cases} B_{UR}^i, & \text{if } B_{UR}^i \leq B_{MAX}, \\ B_{MAX}, & \text{if } B_{UR}^i > B_{MAX}; \end{cases} \quad (2)$$

$$B_D^i = \begin{cases} B_{DR}^i, & \text{if } B_{DR}^i \leq B_{MAX}, \\ B_{MAX}, & \text{if } B_{DR}^i > B_{MAX}, \end{cases} \quad (3)$$

where  $B_{MAX}$  is the maximum transmission window;  $B_{UR}^i$  is

the upstream bandwidth requirement for the  $i$ th ONU;  $B_{DR}^i$  is the downstream bandwidth requirement, which equals to the length of  $Q[i]$  at the time when the OLT starts to do scheduling calculation.

In EATSA algorithm, the control message is separated of data and cycle based, where a cycle is defined as the time elapsed between two pollings of the same ONU. The cycle size can either have fixed or variable length, limited to an upper bound to guarantee a maximum latency. A cycle length is divided into three periods: an update signaling period, a fixed waiting period and a dynamic transmission period. In the first period, OLT polls the ONUs in a round-robin fashion to get ONUs' report message. Once the OLT has received the current report message from all ONUs, it enters the second period and allows the OLT to do DBA calculation. Since EATSA makes scheduling decisions for all ONUs at once, the reports from all ONUs must be received in the previous period. The third period is essentially a giant timeslot used for actual downstream transmission and CW bursts for upstream transmission. Note that the order of ONU's transmission may be different in each cycle and need not be fixed. With the global knowledge of the current bandwidth requirements of upstream and downstream traffic for all ONUs. EATSA can exploit inter-traffic-flow statistical multiplexing. When the load on one traffic flow is light and high on another, the OLT can use the available bandwidth on that lightly loaded traffic flow and reassign it to the highly loaded traffic flow, which therefore, could result in better performance. Here, the total number of traffic flow is  $2N$ . The grant sizing scheme for EATSA may works as follows:

$$B_U^i = \begin{cases} B_{UR}^i, & \text{if } B_{UR}^i \leq B_{MAX}, \\ B_{MAX} + B_{excess}/(2N-K), & \text{if } B_{UR}^i > B_{MAX}; \end{cases} \quad (4)$$

$$B_D^i = \begin{cases} B_{DR}^i, & \text{if } B_{DR}^i \leq B_{MAX}, \\ B_{MAX} + B_{excess}/(2N-K), & \text{if } B_{DR}^i > B_{MAX}, \end{cases} \quad (5)$$

where  $B_{excess}$  is the total excess bandwidth;  $K$  is the number of lightly loaded traffic flows, and they can be computed as

$$B_{excess} = \sum_{i=1}^N (B_{MAX} - B_{UR}^i) | B_{UR}^i \leq B_{MAX} \\ + \sum_{i=1}^N (B_{MAX} - B_{DR}^i) | B_{DR}^i \leq B_{MAX}, \quad (6)$$

$$K = \sum_{i=1}^N 1 | B_{UR}^i \leq B_{MAX} + \sum_{i=1}^N 1 | B_{DR}^i \leq B_{MAX}. \quad (7)$$

## 4 Simulation and analysis

To evaluate the performance of the two proposed algorithms, we undertook a simulation study using an OPNET modeler network simulator. The simulation model consists of an OLT and 16 ONUs. The distances between the OLT and each ONU are randomly distributed over the interval [0.5 km, 20 km], which corresponds to round-trip times ranging from 5 to 200  $\mu$ s. The access link data rate  $R_U$  from users to an ONU is 100 Mbps, and the line rate  $R$  for both upstream and downstream transmissions is 1 Gbps. The guard time is set to 1  $\mu$ s. The size of per-ONU downstream traffic queue at the OLT and the upstream traffic queue at the ONU are all 1 MB. Table 1 summarizes the system parameters used in the simulation experiment reported here.

**Table 1** System parameters

parameter	description	value
$N$	numbers of ONUs	16
$R_U$	line rate of user to ONU link	100 Mbps
$R$	line rate	1000 Mbps
$Q_{ONU}$	queue length at each ONU	1 MB
$Q_{OLT}$	queue length for each ONU at OLT	1 MB
$G$	guard interval	1 $\mu$ s

To model the bursty nature of Internet traffic [8], we generate self similar traffic based on Pareto distribution with a Hurst  $H = 0.8$ , and the size of the generated packets vary between 64 and 1518 bytes. All packets are encapsulated in Ethernet frames before their arrival at the OLT and ONUs, and used as downstream and upstream traffic, respectively. The ratio of traffic arrival rate for OLT and ONU is defined as 2:1.

The performance matrix in our experiments comprises packet delay and average throughput. For each scheduling algorithm, we ran simulations for two different configurations of shared resources, one is with a transmitter and a receiver, and the other is with two transmitters and two receivers, respectively. The maximum total arrival rate for each configuration is set to slightly overload the system.

Figures 3 and 4 compare the average end-to-end delay of upstream and downstream traffic respectively as a function of total arrival rate for two algorithms. Our results in Fig. 3 indicate that at low loads the EATSA algorithm achieves about the same upstream average delay as EATSS algorithm. In the case of one transmitter and receiver, the delay is 281.768 and 347.532  $\mu$ s respectively at rate 100 Mbps; while in the case of two transmitters and receivers, the delay is 241.435 and 308.073  $\mu$ s, respectively, at the same rate. As the rate increases, the delay of EATSA algorithm grows faster, and EATSS algorithm achieves generally lower delays at high rate. For example,

when there is one transmitter and receiver at OLT, it has an average packet delay of 449.999  $\mu$ s for EATSS at load 600 Mbps, and 606.175  $\mu$ s for EATSA. When there are two transmitters and receivers, it has an average packet delay of 739.535  $\mu$ s for EATSS at a rate of 1600 Mbps, while 1249.51  $\mu$ s for EATSA. The reason is twofold. First, EATSA algorithm introduces for some ONUs a delay from the receipt of their request at OLT to the commencement of the scheduling as the OLT is waiting until the requests from all ONUs are received. Second, under the EATSA scheduling, all ONUs experience the inter-scheduling cycle gap, whose length is equal to three parts: the DBA computation time, the transmission time for the CW bursts for the upstream traffic, and the round trip time (RTT) to the first ONU scheduled in the next round.

From Fig. 4, downstream delay results show similar behaviors as well. The reason is the same as that of the upstream delay results discussed previously. At the time in granting upstream traffic, two algorithms also grant downstream traffic as well based on the queue status at

OLT. Therefore, both traffic experiences the same scheduling process.

The average throughputs of an ONU for downstream and upstream traffic are shown in Figs. 5 and 6, respectively. We observe that there is a deviation from the linear behavior in throughput for both directions. This is because the allocated bandwidth for the single selected ONU varies in every cycle according to the bursty traffic load. However, the general trend is on the rise with the total arrival rate. In addition, we can find that the downstream traffic still dominates the whole bandwidth available even taking the traffic ratio into consideration. In the case of one transmitter and one receiver, upstream throughput for the ONU is 23.743 Mbps while downstream throughput is 8.735 Mbps at the rate of 400 Mbps; in the second case, upstream throughput for the ONU is 25.811 Mbps while downstream throughput is 89.943 Mbps. This is because, when making scheduling calculation, OLT knows exactly the length of each downstream queue, while the request message for bandwidth requirement cannot timely reflect

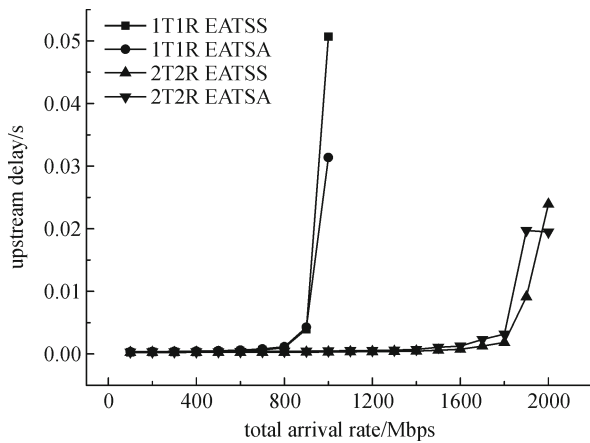


Fig. 3 Upstream delay

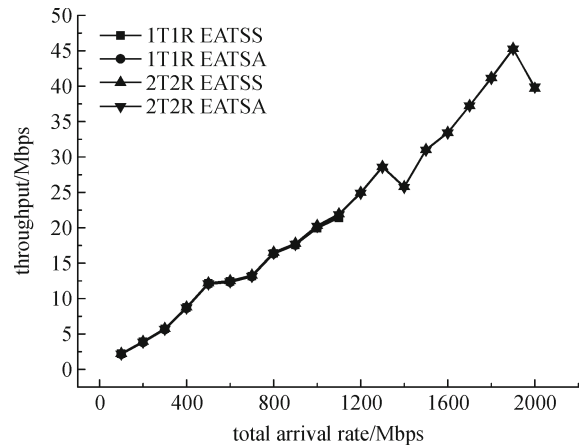


Fig. 5 Average throughput for upstream

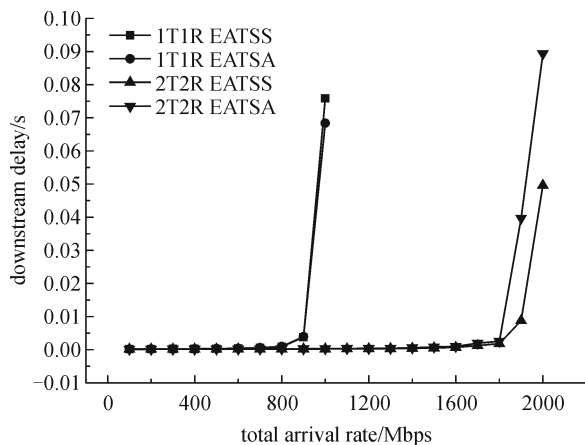


Fig. 4 Downstream delay

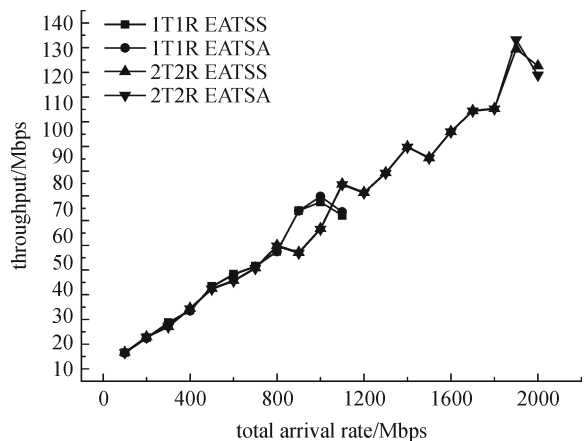


Fig. 6 Average throughput for downstream

the status of ONU's upstream queue, due to the long delay of the "control loop" between the OLT and the users.

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## 5 Conclusion

This paper described a novel cost-effective and easily scalable hybrid TDM/WDM PON based on carrier distributed architecture. All the costly equipments, such as a shared tunable laser and a photoreceiver stack, are located at the OLT. The ONUs, built with an RSOA, are very simple and identical. Two novel scheduling algorithms for this hybrid PON are proposed and their performance in terms of the average packet end-to-end delay and throughput has been studied by simulation. The comparison study shows that, of the two scheduling algorithms, EATSS tends to result in lower packet delays at medium and high traffic loads; on the other hand, EATSA introduces an inter-scheduling cycle gap not experienced by EATSS.

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