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Analysis of IPACT network performance considering channel switch latency for WDM-EPON

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In wavelength-division multiplexing (WDM) ethernet passive optical networks (EPONs), to realize the statistical multiplexing of upstream wavelength resources, some optical tunable components are introduced in the optical network units. However, the switch latency (SL) of these tunable components constrains the performance of WDM-EPON. In this letter, we extend the mathematical model of the WDM interleaved polling with adaptive cycle time (IPACT) scheme by additionally considering the SL conditions. We also investigate the effect of channel SL on network performance. The simulation results show that the performance of WDM-IPACT-SL deteriorates as the SL increases.

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Ethernet passive optical networks (EPONs) have emerged as promising solutions recently due to their inherent advantages, such as longevity, low attenuation, high bandwidth, and cost-sharing among subscribers. However, the access to network traffic has grown explosively with the ever-increasing number of end users and proliferation of emerging applications, such as triple play, video on demand, and so on. Thus, current EPONs that dictate a single channel for both downstream and upstream transmissions are not adequate. Hence, the wavelength-division multiplexing (WDM) EPON, which combines WDM with EPON technology, is a promising upgrade solution to achieve the next-generation scalable and flexible passive optical network (PON)[1,2].

Previous studies on the problem of channel sharing in WDM-EPON usually fall into two categories: static and dynamic wavelength assignments. In static wavelength assignment, each optical network unit (ONU) is assigned a fixed pair of upstream and downstream wavelengths[3]. However, this architecture may not utilize bandwidth efficiently, especially when some wavelengths are overloaded while others have light loads[4]. In dynamic wavelength assignment, all ONUs can have full access to all wavelengths, which necessitates that each ONU transmitter can switch to any designed wavelength channel for upstream transmission. One obvious feature of this category is that each ONU is equipped with one tunable laser, whose tuning speed generally ranges from dozens to hundreds of microseconds[5,6]. Jayasinghe *et al.* proposed another approach to dynamically select the assigned upstream channel from multiple seeding wavelengths by using a tunable filter and a reflective semiconductor optical amplifier[7]. The cost-effective filters mentioned in technological reports also have tuning times in the scale of microseconds[8]. Therefore, the limited tuning speed of these optical components constrains the performance of WDM-EPONs. While the packet length in EPONs ranges from 64 to 1518 bytes, the corresponding transmission time approximately ranges from 0.512 to 12.144 μs on a 1-Gb/s link. Thus, the switch latency (SL) equivalent for the transmission time of a data packet cannot be absolutely neglected while considering the problem of bandwidth management in practical applications of WDM-EPONs, because channel SL has a vital effect on the dynamic bandwidth allocation. However, previously proposed dynamic bandwidth-allocation schemes only focus on the scheduling strategy, without considering the impact of SL on the schedule performances[9].

In this letter, we investigate the effect of channel SL on network-performance parameters, such as average delay and packet-loss ratio, based on the extended WDM interleaved polling with adaptive cycle time (IPACT)[10] scheme. First, we extend the WDM-IPACT scheme incorporating the SL consideration (named WDM-IPACT-SL) and elaborates the operation process of an optical line terminal (OLT). Then, we simulate the performance of the WDM-IPACT-SL model for varying SL values under different simulation conditions.

In the WDM-IPACT-SL scheme, the OLT decides not only to allocate the upstream transmission window in terms of the start time and length, but also to schedule the upstream channel with the first-available wavelength channel (FAWC) scheme for each ONU. In the following text, we describe the detailed explanation regarding how SL is additionally considered into the FAWC scheme. After receiving the GATE message from the OLT, the ONU sends Ethernet frames according to its granted transmission window size on the assigned wavelength channel.

Because the OLT knows the round-trip time (RTT) of all ONUs and keeps track of all upstream channels, it can calculate the next idle time of every upstream channel exactly by using the following equation:

$$t_{\mathrm{Idle}}(C_i) = t^j_{\mathrm{G}}(C_i) + t^j_{\mathrm{T}}(C_i) + t^j_{\mathrm{P(G)}}(C_i) + \mathrm{RTT}^j + B, \quad (1)$$

where $t_{\mathrm{Idle}}(C_i)$ is the next idle time epoch of the channel C_i. We assume that ONU-j is the last ONU assigned on channel C_i to transmit upstream data. Here, $t^j_{\mathrm{G}}(C_i)$ is the time epoch when the last GATE is sent to inform ONU-j to transmit on channel C_i; $t^j_{\mathrm{T}}(C_i)$ is the transmission time spent by ONU-j, which is decided by the transmission-window size assigned by the OLT and the upstream bandwidth of ONU-j; $t^j_{\mathrm{P(G)}}(C_i)$ represents the time required by ONU-j to process the GATE message, which is assumed very small; RTT^j is the RTT of ONU-j; B is the interpacket guard time.

Using Eq. (1), the OLT can calculate the next idle time of all upstream channels. After receiving a REPORT message from ONU-k, the OLT decides the time when ONU-k will transmit on the upstream channel using the following equations:

$$t^k_{\mathrm{ST}}(C_i)=\begin{cases} t_{\mathrm{Idle}}(C_i), \text{ if } C_i=C^k_{\mathrm{Last-round}}, \\ t_{\mathrm{Idle}}(C_i)+\mathrm{SL}, \text{ if } C_i\neq C^k_{\mathrm{Last-round}} \end{cases}, \qquad (2)$$

$$t^k_{\mathrm{EST}}=\min\left\{t^k_{\mathrm{ST}}(C_i), i=1,2,3,\cdots,m\right\}, \qquad (3)$$

where $t^k_{\mathrm{ST}}(C_i)$ is the time epoch when ONU-k can start transmitting on the upstream channel C_i. Equation (2) means that if the upstream channel of ONU-k is switched to another one, the start time of transmission will be delayed by the SL. As shown by Eq. (3), the OLT schedules ONU-k to transmit on the earliest-available channel, among all the channels, at time t^k_{EST}. Then, the OLT will send a GATE message to ONU-k at time $t^k_{\mathrm{G}}(C_{t^k_{\mathrm{EST}}})$, which is calculated as follows:

$$t^k_{\mathrm{G}}(C_{t^k_{\mathrm{EST}}})=\max\left\{\begin{matrix} t^k_{\mathrm{R}}+t_{\mathrm{p(R)}} \\ t^k_{\mathrm{EST}}-\mathrm{RTT}^k \end{matrix}\right., \qquad (4)$$

where t^k_{R} is the time epoch when the OLT receives a REPORT from ONU-k, and $t_{\mathrm{p(R)}}$ represents the time required by the OLT to process the REPORT message. The first expression in Eq. (4) indicates that the OLT cannot send the GATE to ONU-k before the corresponding REPORT from the same ONU is received and processed. The bottom expression in Eq. (4) shows that the OLT schedules the GATE message to ONU-k so that its data arrives at the time epoch t^k_{EST}.

To prevent the monopolization of the upstream channel by a single ONU with high data volume, the limited-assignment scheme is used, where each ONU has an upstream upper-bound limitation, $W_{\max}$. In other words, the OLT will allocate the ONU the bandwidth that it has requested if the requested transmission-window size is smaller than $W_{\max}$; otherwise, $W_{\max}$ will be assigned to the ONU.

Because the channel SL is considered only in the OLT (not in the ONU), Fig. 1 shows the operation process of the OLT according to the WDM-IPACT-SL scheme.

The simulation is carried out using a C++-based simulator, which has been developed through a commercial visual studio platform. We conducted two groups of experimental simulations under two different network-traffic conditions: (1) the traffic load for all the 32 ONUs is identical, ranging from 0.1 to 0.9; (2) the traffic load for each ONU is set randomly in the interval [0.1, 0.9] and the online ONU number varies from 16 to 64. Obviously, the latter group of simulations is much closer to a more practical scenario of networks having heterogeneous traffic loads.

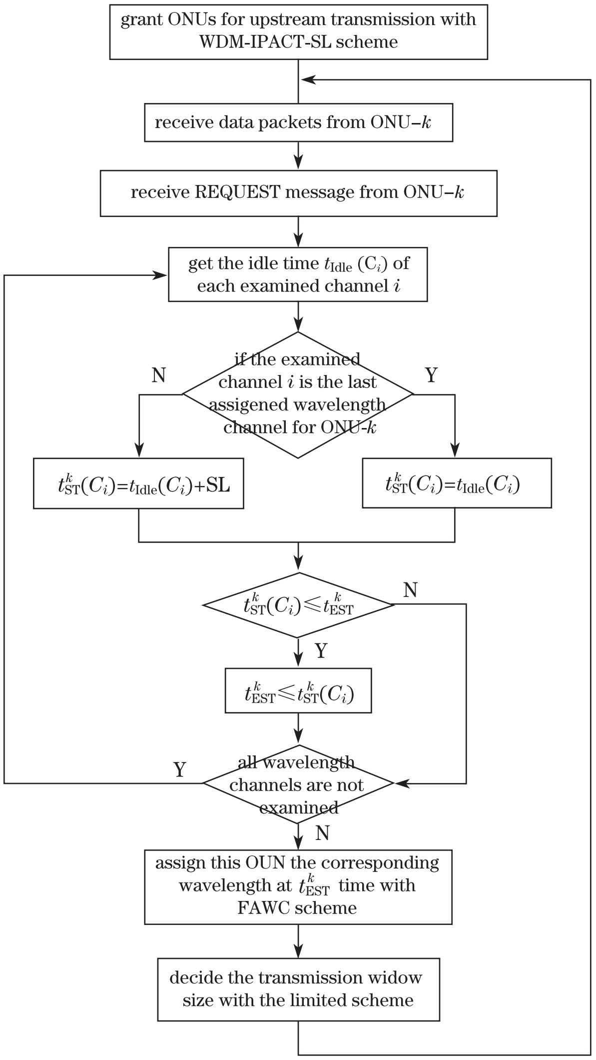

Fig. 1. Flowchart of OLT operation under WDM-IPACT-SL scheme.

In this simulation, a WDM-EPON consists of an OLT and N number of ONUs with three upstream wavelength channels ($m = 3$). The RTT delay for each ONU is assumed to be random (uniform) over the interval [25, 100] μs, which corresponds to the distance between the OLT and the ONUs in the range of 5–20 km. The data-transmission rate of the link from the users to an ONU $R_{\mathrm{D}} = 100$ Mb/s. The upstream data-transmission rate of each wavelength channel R_{U}=1 Gb/s. The upper-bound limitation of the window length $W_{\max}$ is 15,000 bytes when the limited scheme is adopted. Every ONU has a finite buffer size, which is set as 10 Mb. The different SL values are discretely chosen in the range of 10–130 μs. The largest SL value is set to be just more than the transmission time of the $W_{\max}$ with the R_{U} (that is, 15,000 bytes*8/1 Gb/s = 120 μs). Our simulations are conducted using a self-similar traffic source[11], with the Hurst parameter $H = (3 - \alpha)/2$ of 0.8 and the shape parameter α of 1.4. For each simulation, each scheduling result is the average of 100 simulations.

We evaluate the effect of varied SL values on network performance under homogeneous ONU traffic loads. First, the channel-switch ratio (CSR) is defined as the number of channel-switch times divided by the total

GATE number in a simulation lasting 20 s of running time. This parameter shows how frequently the channel switches occur. The more the channel switches, the more is the average packet delay introduced and the more is the deterioration that the network performance suffers. Therefore, we believe that the CSR is an important parameter that dominates over other network-performance parameters of the proposed WDM-IPACT-SL scheme. The CSR performance is first illustrated to facilitate the thorough explanation of other network-performance parameters, such as average delay and packet-loss ratio.

Figure 2 depicts the CSR versus ONU target load with different SL values. We consider the case of SL=0 as the performance baseline, which corresponds to the traditional WDM-IPACT scheme without SL consideration. For each SL case, except for SL=130, the CSR remains almost constant during light loads and abruptly reaches the highest value at heavy loads. The reason is that lower load brings the idle-time epochs for different wavelength channels closer to each other and, consequently, the additional SL reduces the channel-switch time. In contrast, the idle-time epochs of wavelength channels become quite different at heavier loads, which allows for switching to the wavelength channel with the earliest start time, hence the channel switch becomes frequent. We also find that as the SL value increases, the CSR becomes smaller at light loads but reaches the highest value earlier. The reason is that the higher SL will lead to fewer channel switches at low loads. However, when the ONU load increases, the greater delay introduced by higher SLs makes more packets to be buffered at the ONUs, so that the difference between the idle times of channels becomes larger at lighter loads. When SL=130, the CSR is always very low. The largest SL value is larger than the largest transmission window (120 μs) with the limited scheme. This situation reduces the channel-switch time significantly. Thus, the WDM-IPACT-SL almost turns to be a static wavelength-assignment scheme.

Figures 3(a) and (b) show the average packet delay and packet-loss ratio with variations in the ONU load, respectively. We observe that at light loads (less than 0.5), the average packet delay maintains a very low value for all SL values, which hence leads to nearly-zero packet-loss ratio. However, when the ONU load is larger than 0.5, different SL curves are separated with each other. The higher the SL value, the larger the average packet delay becomes, and the average packet delay reaches the highest value earlier than normal, because the CSR also reaches the highest value earlier, as shown in Fig. 2. Because the larger packet delay causes a higher packet-loss ratio, Fig. 3(b) displays the same trend as Fig. 3(a). For SL=130, most channel switches are avoided, and the curve in Fig. 2 is the lowest. Thus, the performance is better than that in most other cases. However, the static wavelength-assignment scheme cannot use the bandwidth effectively in comparison to the dynamic wavelength-assignment scheme. Therefore, for the case of SL=10 (the SL is not large), when the load is smaller than 0.75, the delay in performance is still better than that in the case of SL=130. Nevertheless, at loads above 0.75, when packet loss occurs with increasing traffic, the case of SL=130 shows a better network performance in both Figs. 3(a) and (b). This result indicates that the packet delay with channel SL is significant than the delay with upstream packet congestion in the nearly static wavelength-assignment situation, which corresponds to the case of SL=130.

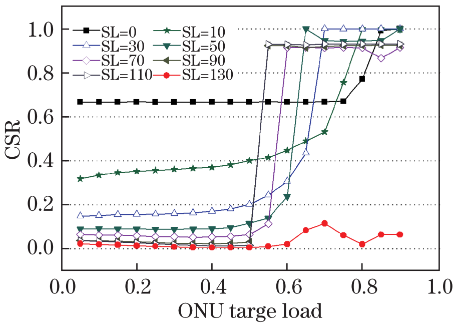

Fig. 2. CSR for different SL values under varying ONU load conditions.

Figure 4 shows the CSRs for different SL values under random ONU loads and varying online ONU numbers. The simulation condition is close to the conditions prevailing in practical applications having heterogeneous

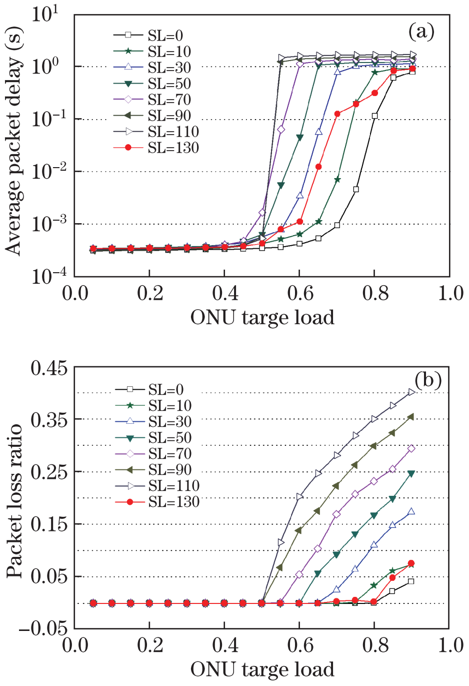

Fig. 3. (a) Average packet delay and (b) packet-loss ratio versus the ONU load for different SL values.

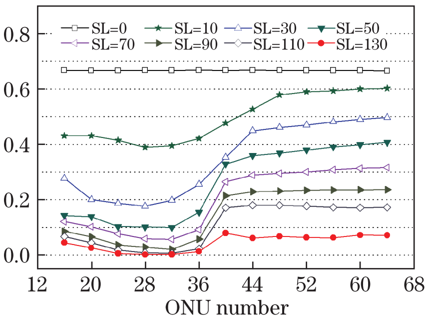

Fig. 4. CSR versus online ONU number for different ONU loads.

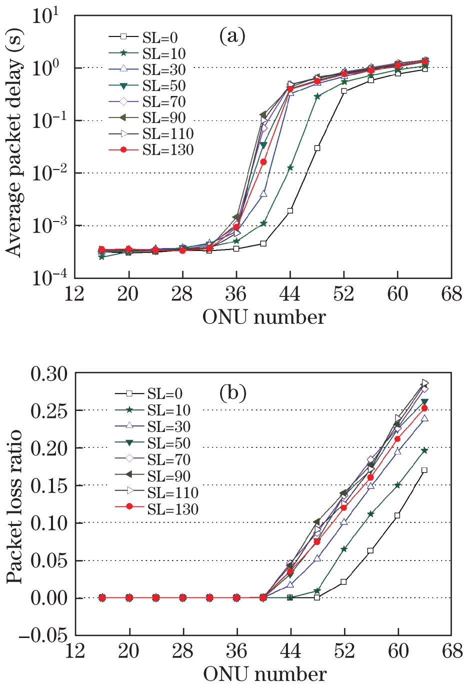

Fig. 5. (a) Average packet delay and (b) packet-loss ratio versus the online ONU number for different ONU loads.

ONU traffic loads. We find that the CSR decreases as SL increases and that the CSR shows almost no difference at approximately 0.67 when the SL = 0 and the CSR is very small, below 0.1, when the SL=130. This is because the larger SL tends to prevent channel switch at a certain degree. We also observe that the increase in the online ONU number represents heavier network-traffic load, which consequently leads to a gradually increasing curve of the CSR, as shown in Fig. 2.

From Fig. 5, we observe that when the online ONU number is small, the average packet delay also has a very low value, and the packet-loss ratio is nearly zero for all the cases of SL. However, for larger online ONU numbers, different SL curves are separated with each other. The higher the SL, the larger is the average packet delay and the packet-loss ratio, because the CSR also reaches larger values, as shown in Fig. 4. The network performance in the case of SL=130 is almost the same as that for SL values greater than 50. This result indicates that large SLs (larger than 50) have the same effect as upstream packet congestion on the network performance in the nearly static-wavelength assignment corresponding to the case of SL=130.

In conclusion, we propose a WDM-IPACT-SL scheme based on an extended WDM-IPACT, combined with SL considerations. We describe a problem formulation for the WDM-IPACT-SL scheme and study the effect of channel SL on network-performance parameters, such as average delay and packet-loss ratio using two groups of simulations. The performance of WDM-IPACT-SL deteriorates as the SL increases. Furthermore, when the SL is greater than the largest window time $W_{\max}$, the WDM-IPACT-SL almost becomes a static wavelength-assignment scheme. It shows better performance than those with SLs larger than 30 μs, which corresponds to 25 percent of the largest transmission-window time. The results also indicate that the WDM-IPACT-SL can adaptively adjust the channel-switch time according to the different SLs and thus reduce the deterioration of network performance during practical applications of the WDM-EPON.

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