doi:10.3788/gzxb20144303.0306001

Recent Research Progress in λ-Tunable WDM/TDM-PON

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Abstract: This paper describes the current research status of the λ-tunable Wavelength-Division Multiplexing/Time-Division-Multiplexing-Passive Optical Network (WDM/TDM-PON). This optical access system realizes new cost-effective operations from the network operator′s point of view. The main feature of the proposed system is that it aggressively exploits wavelength tunability. We classify the system configurations and applications. Then, we describe key technologies, namely newly developed λ-tuning burst-mode transceivers and a widely applicable Dynamic Wavelength and Bandwith Allocation(DWBA) algorithm. Finally, we summarize our research and discuss several issues related to the λ-tunable Wavelength-Division Multiplexing/Time-Division-Multiplexing-Passive Optical Network(WDM/TDM-PON).

Key words: Wavelength-Division Multiplexing/Time-Division-Multiplexing-Passive Optical Network (WDM/TDM-PON); Optical broadband services; Optical communication
OCIS Codes: 060.0060; 060.4510; 060.4264; 060.1810

0 Introduction

Optical broadband services are now widely used throughout the world. Moreover, new attractive services, including wireless off-load, cloud-based big data and high-definition video distribution, are expected. This naturally means that the access network is facing a demand for a huge increase in bandwidth. Another key requirement is a large reduction in operational expenditure (OPEX). High-speed Time-Division-Multiplexing (TDM)-Passive Optical Network (PON) systems have already been developed to increase the guaranteed bandwidth. However, many problems must be overcome if we are to increase the speed of TDM-PON systems to above 10 Gbit/s. The basic problem is finding a way to improve the speed and sensitivity of optical transceivers simultaneously. Higher speed devices, more sensitive photo detectors, higher power lasers, and less expensive optical amplifiers must be developed. On the other hand, high-speed (40G/100G) Ethernet is standardized and Wavelength-Division Multiplexing (WDM) parallel interfaces have been adopted to increase speed inexpensively. So, a reduction in WDM component cost has been expected.

Currently, the standardization of the Next-Generation Passive Optical Network 2 (NG-PON2) is progressing in the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T)/Full Service Access Network (FSAN)[1-2]. The target of NG-PON2 is to increase the aggregate data rate beyond 10G-class-PON (XG-PON). To satisfy this requirement, the basic multiplexing technology of NG-PON2 adopts time- and wavelength-division multiplexing (TWDM)[3]. Each optical line terminal (OLT) communicates with several optical network units (ONUs) through TDM access, while the OLTs use different wavelength pairs. The maximum line rate per wavelength is 10 Gbit/s. However, discussions on how to utilize wavelength tunablity have only just begun.

We have proposed λ-tunable WDM/TDM-PON hybrid multiplexing technologies that improve the guaranteed bandwidth of PON systems using practical technologies and at a practical cost[4-11]. One main characteristic of a λ-tunable WDM/TDM-PON is that it exploits λ-tunablity aggressively and offers some advantages in advanced operation compared with other proposed TWDM-PONs. We have also proposed a Dynamic Wavelength and Bandwidth Allocation (DWBA) technique[12-13] that yields high utilization efficiency and enables a smooth upgrade to a higher bandwidth. The λ-tunable WDM/TDM-PON can be a candidate for NG-PON2 if the standardization organization decides to utilize λ-tunablity in TWDM-PON systems.

Foundation item: Research and development of ultra high speed and low power consumption photonic network technology by the Ministry of Internal Affairs and Communications of Japan

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Received: Oct. 22, 2013; **Accepted**: Dec. 12, 2013

In this paper, we introduce a λ-tunable WDM/TDM-PON system and the status of current research exploiting the advantages of wavelength tunablity. Highly important components are λ-tuning burst-mode transceivers and widely applicable DWBA algorithms. We also discuss the future issue of establishing a cost-effective λ-tuning mechanism allowing cooperation between an OLT and ONUs.

1 System configurations and functional classification of λ-tunable WDM/TDM-PON

We here use TWDM-PON as an abbreviation since it is used in NG-PON2 standardization or for the candidate systems[14] for the NG-PON2. A TWDM-PON includes only a simple "WDM overlaid PON". In contrast, we define our λ-tunable WDM/TDM-PON as a wavelength multiplexed TDM-PON system that aggressively exploits a λ-tuning mechanism. This section introduces the configurations of λ-tunable WDM/TDM-PONs, and functional advantages for realizing cost-effectiveness from several operational points of view.

1.1 Configuration of λ-tunable WDM/TDM-PON

Fig. 1 shows the configuration of the λ-tunable WDM/TDM-PON. An OLT consists of interface cards (IFs), a DWBA controller, a MUX/DEMUX and a Photonic Router (PR). The IFs output optical downstream signals and receive optical upstream signals from λ-tunable Optical Network Units (ONUs). Each IF uses a different wavelength of the downstream/upstream pair ($\lambda_{1d,u} \sim \lambda_{3d,u}$). The PR transfers each wavelength to a designated port and connects IFs to PON branches. A MUX/DEMUX multiplexes upstream signals to an edge router and demultiplexes the downstream signal to each IF. These multiplexing/demultiplexing operations are executed according to the frame destination. The edge router acts as the interface between OLT and the core/metro networks. Some λ-tunable ONUs and some IFs have λ-tunable transceivers that transmit upstream signals and receive downstream signals. They can change their assigned IF and λ-tunable ONU by tuning their own wavelengths. The DWBA controller calculates and controls the assignment of λ-tunable ONUs with a DWBA algorithm. The DWBA controller sends messages requesting changes to ONU wavelength pairs. ONUs that receive the message tune the directed wavelength pair. The DWBA controller also directs the MUX/DEMUX to change the transferring port according to a new assignment of the λ-tunable ONUs. The DWBA controller monitors the upstream/downstream traffic if needed. The difference between the proposed system and a simple "WDM overlaid PON" system is the adoption of a λ-tunable function in the ONUs and the IFs. The OPEX reduction is realized by using this λ-tunable mechanism.

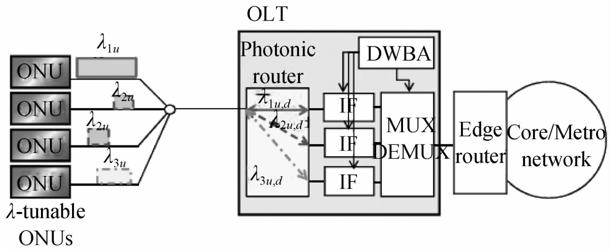
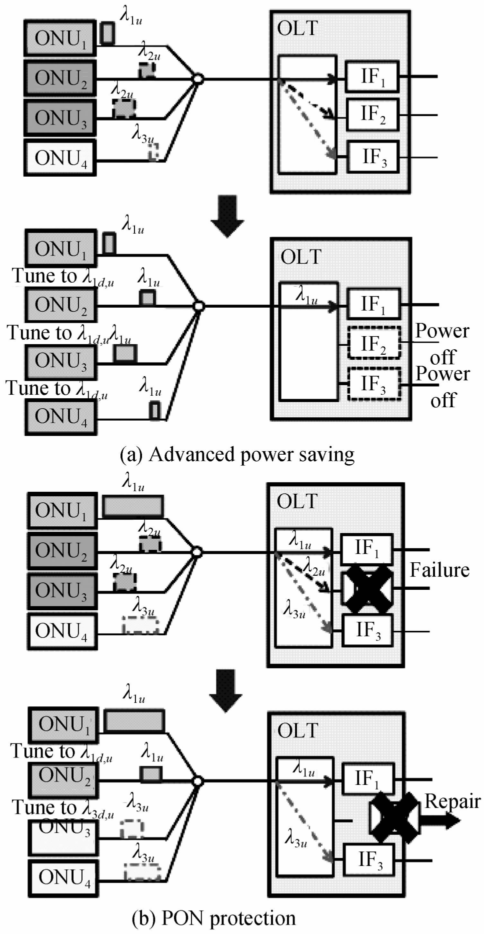
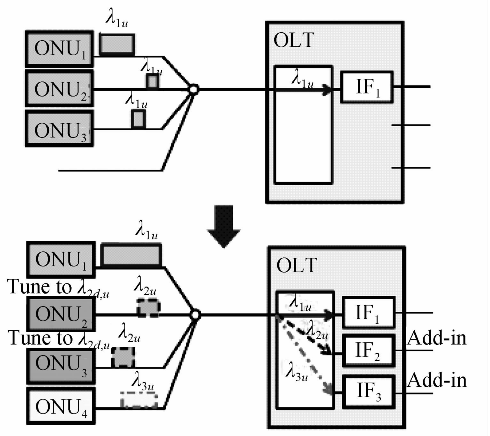


Fig. 1 Configuration of λ-tunable WDM/TDM-PON

1.2 λ-tunable functions and applications

By utilizing λ-tunability, we obtain several advantages in network operations. Fig. 2 shows the three main advantages. The upper part of each figure shows the situation before the functions are activated, and the bottom part shows the situation after activation. We assume that each ONU can use wavelength pairs $\lambda_{1d,u} \sim \lambda_{3d,u}$ and that the OLT has three IFs, $IF_1 \sim IF_3$, to which the wavelength pairs $\lambda_{1d,u} \sim \lambda_{3d,u}$ are assigned, respectively. ONUs 1, 2, 3 and 4 are assigned to IF_1, IF_2, IF_2 and IF_3, respectively.





(c) Incremental upgrade

Fig. 2 Main advantages of λ-tunable WDM/TDM-PON

First, Fig. 2(a) describes advanced power saving. When there is less traffic, the wavelengths of all ONUs are changed to $\lambda_{1d,u}$ to be connected to IF$_1$. Then the other IFs (IF$_2$, 3) of the OLT can be forced to sleep. This can eliminate excess power consumption by IFs. Next, Fig. 2(b) shows PON protection. When an IF (IF$_2$) has failed, ONU2, 3 that are assigned to IF$_2$ cannot continue their communication. The OLT lets the ONUs change their wavelengths to normal IFs. With Fig. 2(b), ONU 2, 3 change their own wavelength pair to $\lambda_{1d,u}$ and $\lambda_{2d,u}$, respectively. Then, ONU2, 3 recover and continue communication with the core/metro network even if IF$_2$ is under repair. Finally, Fig. 2(c) depicts incremental upgrade, which is also called pay as you grow. At the first installation of IF$_1$, we assume there are fewer ONUs (ONU$_1$, 2, 3). After the addition of ONU$_4$ or an increase in the total amount of traffic, the total bandwidth can be increased incrementally by installing additional IFs (IF$_2$, 3). Assuming a situation where the bandwidth of ONU$_1$ increases, we can assign ONU$_4$ to the added IF$_4$ and re-assign ONU$_2$, 3 to IF$_2$ by tuning to $\lambda_{2d,u}$. Therefore, we can quickly double, triple, or quadruple the total bandwidth on demand.

There are other functions than those described in the Fig. 2. One is called colorless. The ONUs tunability can be used to alleviate inventory management in WDM-PONs. When an ONU is connected to a network, a wavelength pair of the ONU is appropriately tuned allow it to communicate with the designated IF. This eliminates improper connections between the colored ONU and the OLT. This feature is essential if we are to realize cost-effective ONUs. The highly advanced functions are load balancing and dynamic wavelength and bandwidth assignment. With load balancing, when the traffic of one IF is heavily congested, the OLT changes the wavelength pairs of some ONUs to others and assigns them to other vacant IFs. Dynamic wavelength and bandwidth assignment always optimizes assigned wavelength pairs and timeslots to improve the usage efficiency of the wavelength pair and provide bandwidth according to user demand. In realizing these two functions, the DWBA function in the OLT must monitor all the traffic passing through the IFs and requires an algorithm to calculate which ONU has to change the assigned IF and when.

Wavelength tunability requirements, namely tuning frequency and tuning speed, differ depending on the function. For example, advanced power saving requires the number of active IFs to be controlled according to the amount of upstream/downstream traffic. It changes the assigned wavelength pair of ONUs daily or hourly, and the tuning must occur quickly (in several milliseconds). On the other hand, PON protection assumes that IFs have failed. Therefore, λ-tuning does not occur frequently, but the tuning must be very fast in the several nsec to several msec range to protect the traffic as far as possible. An incremental upgrade occurs rarely and a slow tuning speed can be acceptable. A load balancing assumes heavy congestion. λ-tuning occurs rarely, but the tuning must be fast (in several milliseconds). A dynamic wavelength and bandwidth assignment occurs frequently to optimize traffic. It requires very fast tuning speed to protect the traffic as far as possible. Table 1 summarizes the advantages mentioned above and the λ-tuning frequency and speed requirements. It is clear that the more reliable and faster tuning transceiver is applicable to all functions. Therefore, it is very important to devise/select an appropriate transceiver for realizing both the lowest cost and the fastest tuning speed.

2 λ-tunable burst-mode transceiver

2.1 Classifications of λ-tunable transceivers

The configuration of the λ-tunable transceiver differs depending on PR type. The PRs must properly route upstream wavelengths to IFs and downstream wavelengths to ONUs. This routing function is realized by a combination of optical broadcasting and optical filtering. Fig. 3 show three possible configurations that depend on PR type.

In Fig. 3(a) a Power Splitter (PS) is used as the PR. The upstream signals from the ONUs are broadcast by the PR to all IFs. All downstream signals from IFs are also broadcast to all ports on the ONU side. The transceiver of each IF has a WDM to multi/demultiplex upstream and downstream optical signals. The receiver part of the transceiver has a fixed optical filter (F) that allows the assigned upstream wavelength

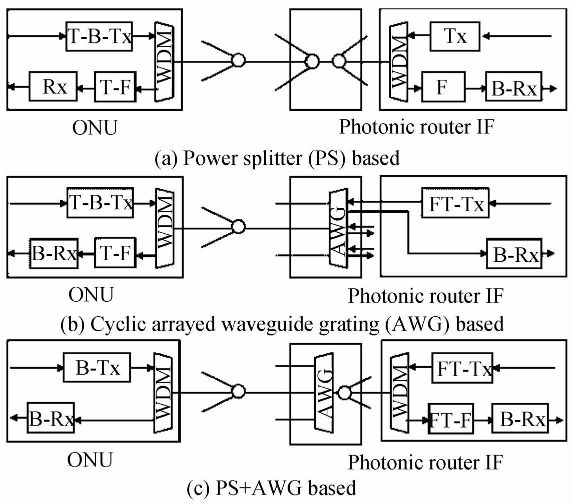


Fig. 3 Transceiver configurations corresponding to each type of photonic router

of each IF to pass. The IF receiver must be a burst-mode receiver (B-Rx) because the upstream signal of each assigned wavelength is the same as that of the TDM-PON. On the other hand, the transceiver of each ONU has λ-tunability in the transmitter and receiver. The ONU transmitter is a λ-tunable burst-mode transmitter (T-B-Tx) that changes its own wavelength and sends bursty upstream signals in the same way as the TDM-PON. The receiver of the ONUs has a λ-tunable filter (T-F) that allows only the assigned downstream wavelength to pass. The ONU receiver is a continuous-mode receiver (Rx), which is the same as that of the TDM-PON. The advantage of this configuration is that it consists of the simplest PR components. In addition, we can utilize the existing Optical Distribution Network (ODN) of PONs.

In Fig. 3(b) a cyclic Arrayed Waveguide Grating (AWG) is used as a PR. With this type of PR, each wavelength from a port on the IF side travels to a port on the ONU side. Because the cyclic AWG can filter the optical signal, the filter (F) in the IF receiver at a PS-based configuration in Fig. 3(a) can be eliminated. However, the combinations of transparent wavelengths between an output port and an input port of the cyclic AWG are fixed. The advantage of using the cyclic AWG is that AWGs have less attenuation than PSs. The larger number of ONUs that are connected to the OLT, the more the advantage is enhanced. On the other hand, to communicate with all the ONUs connected to the PR, the IF transmitter must change its downstream wavelength according to the destination ONU of the downstream frames. This requires a fast (frame-by-frame) tunable transmitter (FT-Tx).

As a result, the IF transceiver configuration becomes complicated. Also, the downstream signal is filtered at the ONU receiver to eliminate unnecessary signals at other different wavelengths. The signals received at the ONUs to become bursty. Therefore, the ONU receiver must have a burst-mode (B-Rx) configuration instead of a T-F and an Rx in the PS-based configuration.

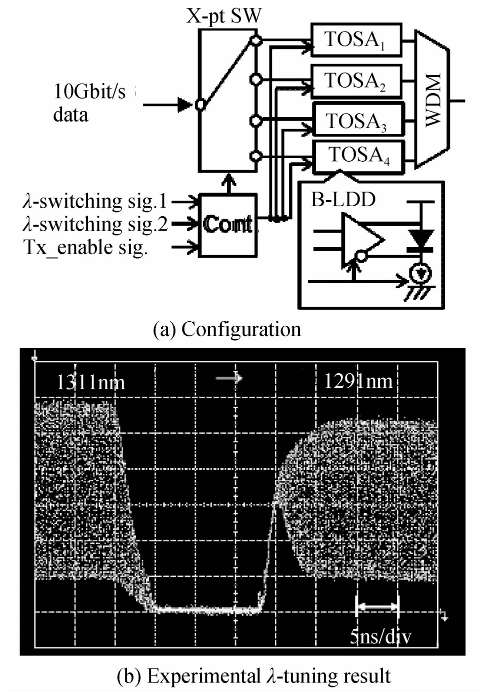
In Fig. 3(c), a PS and an AWG are combined. And the AWG plays the role of a wavelength filter. The upstream signals are broadcast to all IFs. The output wavelength in each downstream port of the AWG is fixed. The advantage of this configuration is that it is the simplest ONU transceiver. It requires a WDM, a B-Tx and a B-Rx. On the other hand, this means that we cannot apply the colorless function for inventory management since output wavelengths are fixed at every ONU side port of the AWG. In this configuration, each upstream signal from ONUs has a different wavelength frame-by-frame. Therefore, an IF receiver requires a fast tunable filter (FT-F) to receive the variable wavelength of upstream signals. This causes difficulties and makes the cost of the IF transceiver higher than that of the cyclic AWG based configuration shown in Fig. 3(b).

2.2 Demonstrations of λ-tunable burst-mode transceivers

One of the keys to realizing a λ-tunable WDM/TDM-PON is to realize a λ-tunable transmitter as well as a wavelength selectable receiver, especially for low-cost ONUs. As summarized in Table 1, a fast λ-tuning speed is very attractive in terms of advanced power saving, PON protection, load balancing and dynamic wavelength and bandwidth assignment. On the other hand, a slow tuning speed, e. g., several seconds, is still useful in terms of the incremental upgrade and colorless requirements. To meet all tunability requirements shown in Table 1, we have developed a cost-effective λ-tunable burst-mode transceiver[8-11]. For example, Fig. 4(a) shows the configuration of the developed T-B-Tx[9], which has 4-TOSAs, a 1 x 4 cross point switch (X-pt SW), a WDM filter, and a controller. Each TOSA is newly equipped with a directly modulated laser diode at a different wavelength and a burst-mode LD driver (B-LDD). In this configuration, the X-pt SW outputs a 10-Gbit/s data signal and the controller outputs a Tx_enable signal that controls the bias current and modulation current of the LD in TOSAs, and the λ-switching signal, which selects the correspondingTOSA. The T-B-Tx outputs an upstream signal at the appropriate wavelength at a timeslot according to the Tx_enable signal. Fig. 4(b) shows the output signal waveforms. The λ-switching and burst rise time was less than 30 ns. The burst turn off time was less than 10 ns.

Table 1 Advantages and corresponding requirements of λ-tuning ability

Function	Tuning frequency	Tuning speed
Colorless ONU	Low (only initialization)	Slow (second order)
Advanced power saving (OLT-port sleep)	Medium (per hour or day)	Medium (msorder)
PON protection	Low (OLT-port failure)	Fast (ns-ms order)
Incremental upgrade (Pay as you grow)	Low (only initialization)	Slow (second order)
Load balancing	Low (per day or week)	Medium (msorder)
Dynamic wavelength and bandwidth assignment	High (frame by frame)	Fast (ns-ms order)



(a) Configuration

(b) Experimental λ-tuning result

Fig. 4 Configuration and experimental results for the developed λ-tunable transmitter

Fig. 5 shows the waveforms of electrical signals received at each B-Rx of the IFs[9]. In this experiment, we assumed the use of a cyclic AWG base configuration and developed an AWG that multi/demultiplexes the 1.3 μm upstream and 1.5 μm downstream signals. The transmitted burst pattern consisted of blocks of 397 ns preambles, a 1 589 ns payload with a 2^{31}-1 PRBS, and a 99 ns end of burst. The optical signals multi/demultiplexed by the cyclic AWG router were received instantaneously by each B-Rx and no waveform distortion was observed. We have showed a transceiver operation in a recent experiment[11] on the PS-based configuration. We adopted a same transmitter configuration to the recent experiment. In this experiment, we have succeeded wavelength switching time of less than 100-ns on both of transmitter and receiver operation. These experimental results showed the feasibility of meeting all the high-speed tuning requirements shown in Table 1.

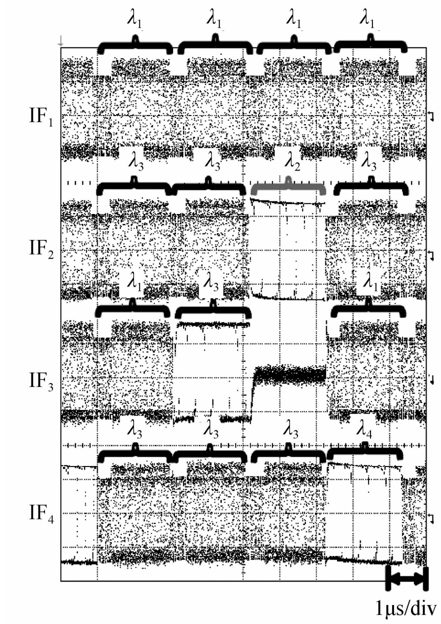


Fig. 5 Experimental upstream transmission results

3 Proposal of DWBA algorithm

The load balancing and the dynamic wavelength and bandwidth assignment in Table 1 are realized with a DWBA algorithm that automatically distributes ONU traffic passing through each IF. In the upstream signal, the DWBA algorithm should combine dynamic bandwidth allocation (DBA) and the wavelength tuning of the ONUs. There are three important requirements for the DWBA considering the fact that the λ-tuning time of an ONU transceiver:

1) The DWBA controller usually assigns the upstream slots of ONUs at a DBA cycle. It is important for the cycle to be short from the standpoint of the upstream transfer delay and precise bandwidth control. Therefore, the DBA cycle should not be extended.

2) We introduced a high-speed tuning transmitter in the previous section. However, there are many candidates for the λ-tuning device. As regards the cost-effectiveness of the transceiver, we should consider a feasible DWBA with various devices. According to Ref. [15], the λ-tuning time of most transmitters is around 10 ms including future expectation. This period is much longer than the DBA cycle of 125 μs of a Gigabit-capable PON (GPON) or the 2 ms of an Ethernet PON (EPON)[16]. Therefore, load balancing and dynamic wavelength and bandwidth assignment must take account of the λ-tuning time to maintain the DBA performance.

3) The DWBA controller must also handle

automatic load balancing. When the total upstream bandwidth of an IF is increased and immediately before overflow occurs, the DWBA controller detects the situation, decides the ONU to be tuned and the destination IF to which the ONU will be newly assigned. If there is unnecessary λ-tuning, it may not only cause an interruption of the λ-tuned ONU traffic, but also disturb the traffic of the other ONU of the newly assigned IF. The DWBA controller has to decide that the ONU should definitely be tuned and has to minimize the number of λ-tuning iterations to avoid unnecessary λ-tuning.

In this section, we introduce our proposed upstream DWBA algorithm that adopts effective load balancing while taking a reasonable λ-tuning time into consideration[13]. Fig. 6 shows the proposed sequence for requirements 1) and 2) where ONU_1, which belongs to IF_1, is going to switch to IF_2. ONU_1 is going to tune from $\lambda_{1d,u}$ of IF_1 to $\lambda_{2d,u}$ of IF_2. Here, we define a new DWA cycle where the period is several times longer than the fixed DBA cycle. The DWA cycle is determined to ensure that all the λ-tunable transceivers can finish λ-tuning in a DWA cycle. The DWBA controller determines and directs the ONU tuning in each DWA cycle. Once the DWBA algorithm has decided the λ-tuning in the DBA+DWA calculation at the top of the DWA cycle, IF_1 sends a Gate frame including a tuning direction to $\lambda_{2d,u}$. ONU_1 starts tuning once it receives the Gate frame and returns a Report frame including a message stating that tuning is complete. Then IF_2 starts to allocate upstream bandwidth using DBA.

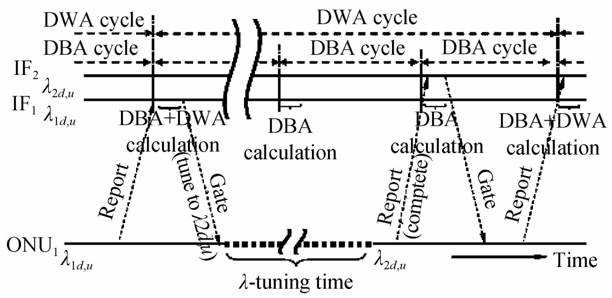
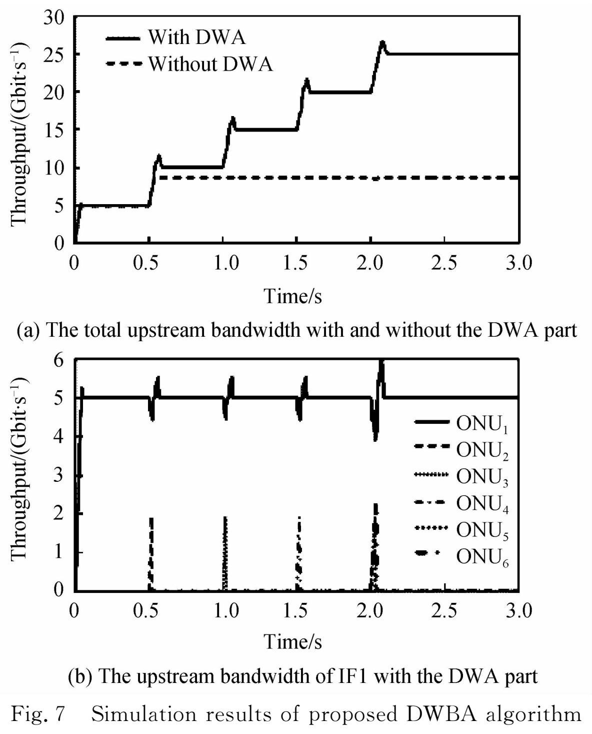


Fig. 6 Proposed wavelength tuning sequence

In Ref. [13], we detailed our DWBA algorithm that satisfies requirement 3). The proposed DWBA consists mainly of two blocks, namely the DBA part and the DWA part, which are executed during each DBA and DWA cycle, respectively, as shown in Fig. 6. The DBA part allocates the upstream slots for each IF. If the total slot size requested from ONUs in a DBA cycle exceeds the slot size that can be allocated by each IF, the DBA part performs fair sharing of the upstream bandwidth[17]. In contrast, this situation indicates that the load balancing function, namely λ-tuning is probably required. The DWA part calculates and decides whether an ONU should switch.

We conducted simulations to confirm the efficacy of the proposed DWBA algorithm. We assume that a 40-Gbit/s λ-tunable WDM/TDM-PON system consists of four wavelength pairs each multiplexed at a bit-rate of 10 Gbit/s. There are four IFs and six ONUs. All ONUs are initially assigned to IF_1. The DBA and DWA cycles are 2 and 10 ms, respectively. The ONU wavelength tuning time is 10 ms or less. The entire 25 Gbit/s upstream traffic from the ONUs is inputted in series at 0 s (ONU_1 at 5 Gbit/s), 0.5 s (ONU_2 at 5 Gbit/s), 1 s (ONU_3 at 5 Gbit/s), 1.5 s (ONU_4 at 5 Gbit/s) and 2 s (ONU_5, 6 at 2.5 Gbit/s). Fig. 7(a) shows simulation results for the total upstream bandwidth provided by the proposed DWBA with and without the DWA part. Without the DWA part, the total throughput is limited in terms of the maximum upstream bandwidth of the IF_1. On the other hand, our proposed DWA could extend the total upstream bandwidth automatically. Fig. 7 (b) shows the throughput of each ONU at IF_1 with the DWA part. The DWA part judged the congestion of IF_1 and executed the λ-tuning of ONU2, 3, 4 and (5, 6) at 0.5 s to IF_2, 1 s to IF_3, 1.5 s to IF_4 and 2 s to IF_2 and IF_3, respectively. The throughput of ONU_1 was kept at 5 Gbit/s. All the ONUs are properly distributed and remain stable after each λ-tuning has been undertaken. These results showed that our proposed DWBA algorithm can handle both the DBA and upstream load balancing appropriately even if the λ - tuning time is much longer than the DBA cycle.



(a) The total upstream bandwidth with and without the DWA part

(b) The upstream bandwidth of IF1 with the DWA part

Fig. 7 Simulation results of proposed DWBA algorithm

4 Discussion and conclusion

This paper introduced the current research status of the λ-tunable WDM/TDM-PON in terms of cost-effective operation from the network operator's point of view.

In section 1, we described the network configuration and six attractive functions of the λ-tunable WDM/TDM-PON. We also classified the configurations of OLT/ONU transceivers according to three types of PR. The key feature of the proposed λ-tunable WDM/TDM-PON system is that it aggressively exploits wavelength tunability. By switching the assigned wavelength pair of ONUs, we can realize such functions as advanced power saving, PON protection, incremental upgrade and so on. These functions will contribute to the reduction of the network operator's OPEX. The advantages of the system are essential supplement for the TWDM-PON standardized by ITU-T. FSAN is discussing NG-PON2 based on the existing ODN architecture. Hence, the transceivers with a PS-based configuration shown in Fig. 3(a) are suitable for NG-PON2.

As described in section 2, the first and most important research issue is how to make a cost-effective λ-tunable transceiver. This means that it is important both how fast T-B-Tx and T-F can switch their wavelengths and how cost-effective a transceiver we can develop. If faster switching is realized, more of the functions in Table 1 become feasible. However, a low cost but slow switching transceiver will prevent us from realizing dynamic wavelength and bandwidth assignment because a long switching time will lead to disruption of traffic or loss of transmission signal. To exploit all the advantages of the λ-tunable WDM/TDM-PON, we must pursue both cost-effectiveness and a fast tuning speed. Our proposed transceiver has four transmitters and four receivers with which to realize ultra-fast (less than 100-ns[11]) switching. This configuration is also commonly employed in the transceiver for the 40-Gbit/s Ethernet standard. We assume that high-speed Ethernet technology will become widely used, and so the cost of the proposed transceiver will become sufficiently low.

We have also proposed a λ-tuning procedure and a new upstream DWBA algorithm that combines DBA and DWA in section 3. Our proposed DWBA algorithm can switch the ONU assignment according to the upstream traffic load of each IF. The algorithm detects congestion and decides an ONU and an appropriate IF to be re-assigned. Then the directed ONU switches its own wavelength pair. We have simulated our proposed algorithm and shown that the algorithm can detect congestion correctly and handle transceivers with a long switching time of 10 ms. However, to the best of our knowledge, there has been no demonstration report of a millisecond order λ-tuning protocol. Therefore, the second research issue with the λ-tunable WDM/TDM-PON is experimentation or demonstration of the proposed wavelength procedures. Furthermore, we have not discussed about handling downstream traffic. Finding a way to avoid any disruption of downstream traffic during λ-tuning should also be studied.

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