Enabling Technologies for Future Scalable and Flexible WDM-PON and WDM/TDM-PON Systems

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(Invited Paper)

***Abstract*—Wavelength-division multiplexing (WDM) technologies are expected to play a key role in realizing the next generation scalable and flexible passive optical networks (PONs). One candidate is WDM-PON, in which each optical network unit (ONU) uses a different wavelength, i.e., a unique wavelength, in each direction to communicate with the optical line terminal. Another candidate is WDM/time-division multiplexing (TDM)-PON; it combines WDM with TDM technology. This paper reviews recent state-of-the-art research on the enabling technologies needed to realize future WDM-PON and WDM/TDM-PON systems, and discusses future directions toward practical PON systems.**

***Index Terms*—Optical communication, optical subscriber loops, passive optical networks, wavelength-division multiplexing.**

I. Introduction

MASSIVE deployment of fiber to the home (FTTH) is underway to accommodate the explosion in bandwidth demand driven by the extreme growth in Internet services [1]. FTTH is typically realized by gigabit-class passive optical network (PON) systems, such as gigabit Ethernet PON (GE-PON) standardized by IEEE [2] and gigabit-capable PON (G-PON) standardized by ITU-T [3]. Both GE-PON and G-PON provide a point-to-multipoint access between one optical line terminal (OLT) and several optical network units (ONUs) through the use of time-division multiplexing (TDM) to pass downstream signals from the OLT to the ONUs, and time-division multiple access (TDMA) to multiplex upstream signals from the ONUs to the OLT. IEEE recently completed the standardization of 10 Gbit Ethernet PON (10 Gbit-EPON) systems to prepare for a further bandwidth explosion [4], and ITU-T has started standardizing the 10 Gbit-capable PON (XG-PON) [5]. In these systems, the speed of TDM/TDMA is increased to around 10 Gbit/s for downstream signals, while it is likely that several bit rate options will be standardized for upstream signals. In gigabit-class and 10 Gbit-class PON systems, wavelength-division multiplexing (WDM) is used for directional multiplexing, i.e., to multiplex upstream and downstream signals, as well as service multiplexing, e.g., to multiplex a video-distribution signal onto a PON system [6].

Manuscript received September 1, 2009; revised September 30, 2009; accepted October 16, 2009. Date of publication December 4, 2009; date of current version October 6, 2010.

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Digital Object Identifier 10.1109/JSTQE.2009.2035640

The full service access network initiative (FSAN), which proposed G-PON to ITU-T, is studying the following two solutions for the next generation PON (NG-PON) [7]:

1) NG-PON1 allows coexistence with gigabit-class PONs in the same optical distribution network (ODN) as the middle-term solution; and
2) NG-PON2 allows the use of a new ODN as the long-term solution.

Note that, ODN is defined as the fiber plus the power splitter(s) put between OLT and ONUs. While the XG-PON has been chosen as the NG-PON1 solution, new PON systems based on advanced WDM technologies are among the NG-PON2 candidates under study.

One example of the new PON systems based on advanced WDM technologies is the WDM-PON, in which each ONU uses a different wavelength, i.e., an independent wavelength, in each direction to communicate with the OLT. Another example is the WDM/TDM-PON, in which a number of wavelengths are used in each direction to link the OLT to a number of ONUs; each wavelength is shared among several ONUs rather than being dedicated to a single ONU. Such advanced WDM-based PON systems can be alternatives to higher speed TDM-based PON systems, i.e., higher than 10 Gbit/s, for future PON systems.

While keeping the aforementioned trend in practical PON systems in mind, this paper reviews the state-of-the-art technologies needed to realize the future scalable and flexible PON systems based on WDM. In Section II, advanced WDM-based PON systems are categorized into three types of architecture: WDM-PON, static WDM/TDM-PON, and dynamic WDM/TDM-PON. Each is then defined, and typical configurations and the features of each are described. Based on the categorization, Sections III, IV, and V review the enabling technologies for the three architectures. Furthermore, future directions of practical PON systems are discussed based on the WDM-PON and WDM/TDM-PON technologies in Section VI; a summary of this paper is provided in Section VII.

II. WDM-PON and WDM/TDM-PON Architectures

Prior to describing the state-of-the-art enabling technologies for future WDM-PON and WDM/TDM-PON systems, this section categorizes these systems into the following three architectures: 1) WDM-PON; 2) static WDM/TDM-PON; and 3) dynamic WDM/TDM-PON. The following summarizes the definition, typical configuration, and features of each architecture.

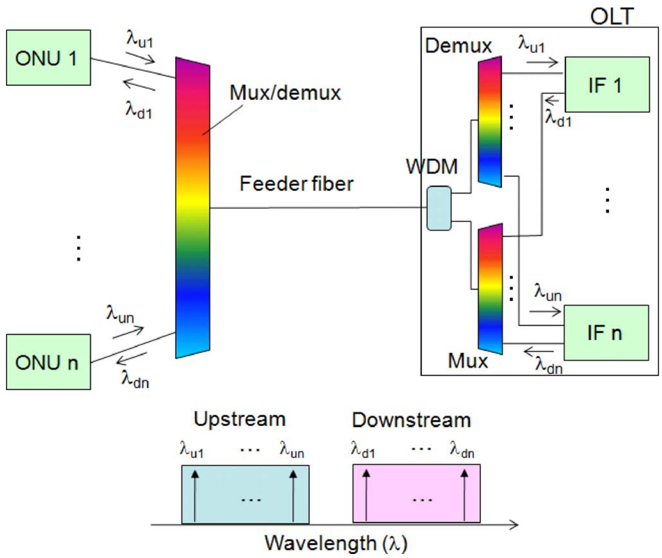

Fig. 1. Typical configuration of WDM-PON system.

A. WDM-PON

In this paper, WDM-PON is defined as a PON system in which each ONU uses a different wavelength, i.e., a unique wavelength, in each direction to communicate with the OLT. Fig. 1 shows a typical WDM-PON configuration. ONU k ($k = 1$ to n) emits the upstream signal with wavelength λ_{uk} and receives the downstream signal with wavelength λ_{dk}. To achieve the wavelength multiplexing of upstream signals from λ_{u1} to λ_{un} as well as the wavelength demultiplexing of downstream signals from λ_{d1} to λ_{dn}, a wavelength splitter/router is typically used as the optical branching device instead of the power splitter used in TDM-based PON systems. The OLT hosts n interface cards (IF 1 to n).

The most unique feature of this architecture is that point-to-point communication is facilitated between IF k and ONU k logically. Therefore, this type of WDM-PON system is sometimes called the "virtual point-to-point" system.

B. Static WDM/TDM-PON

Static WDM/TDM-PON is defined, in this paper, as a PON system in which several wavelengths can be used in each direction to realize communication between the OLT and a number of ONUs, each wavelength can be shared by several ONUs, and the wavelength(s) assigned to an ONU remain unchanged from installation until disconnection. The optical branching device is typically a power splitter, or a combination of a power splitter and a wavelength filter/router.

WDM overlay (or WDM stacking) of several TDM-PON systems is one example of the static WDM/TDM-PON system: each TDM-PON uses a different wavelength, therefore, the total capacity of the feeder fiber can be increased [8]. Fig. 2 shows the generic architecture for the static WDM/TDM-PON system. ONU $j1$ to ONU jn ($j = 1$ to m) access the same interface card (IF j) in the OLT by using the same wavelength, i.e., λ_{uj} and λ_{dj} for upstream and downstream, respectively. Namely, m is the number of TDM-PONs stacked/overlaid by WDM. Therefore, there are m interface cards (IF 1 to m) in the OLT side.

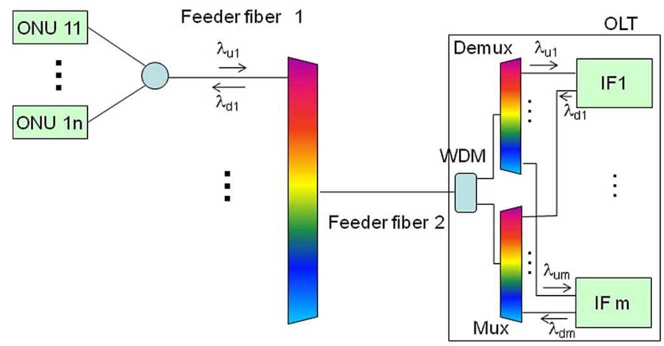

Fig. 2. Example configuration of static WDM/TDMA-PON system.

This architecture is especially effective if one wants to extend the reach of "feeder fiber 2" in Fig. 2 because the fiber cost, which basically increases with the reach, can be shared among the high number of ONUs. Node consolidation using long-reach optical access systems is an effective way for network operators to decrease the operational expenditure (OPEX) provided system cost, i.e., capital expenditure (CAPEX), is sufficiently low [9]. In this approach, "feeder fiber 1" in Fig. 2 constitutes the section between the subscriber's home and the nearest central node, and "feeder fiber 2" the section between the central node and a consolidation node. The distances typical of the former and the latter sections are 10–20 km and 40–80 km, respectively.

C. Dynamic WDM/TDM-PON

Dynamic WDM/TDM-PON is defined in this paper as a PON system in which several wavelengths can be used in each direction to establish communication between the OLT and a number of ONUs, each wavelength can be shared by several ONUs, and ONU wavelength assignment can be dynamically changed during communication/operation [10]. Fig. 3 shows an example of this architecture. The system comprises ONU 11 to ONU *Mn*, IF 1 to IF N in OLT, M power splitters, and an M-by-N passive wavelength router. ONU *jk* accesses port j of the wavelength router via power splitter j ($j = 1$ to M, $k = 1$ to n). Note that M is the number of power-splitter branches, N is the number of IF cards, and n is the number of ports of every power splitter. This system allows each ONU to access every IF by using a wavelength tunable laser diode (TLD) as the transmitter: e.g., ONU $1k$ can access IF 1, 2, ..., N by using $\lambda_{u1}, \lambda_{u2}, \ldots, \lambda_{uN}$, respectively. Arrayed waveguide gratings (AWGs) can be used as the wavelength router; they offer cyclic wavelength-transfer, so ONU $2k$, $3k$, ..., *Mk* can access all IFs by using the appropriate wavelength among $\lambda_{u1}, \lambda_{u2}, \ldots, \lambda_{uN}$ as well. The same criteria can be adopted for downstream signals: λ_{uk} and λ_{dk} are always used as a pair as shown in the figure ($k = 1$ to N), so that each ONU always receives its downstream signal from the IF card that the ONU sends its upstream signal to. In this case, a tunable filter (TF) is necessary at the ONU for wavelength selection.

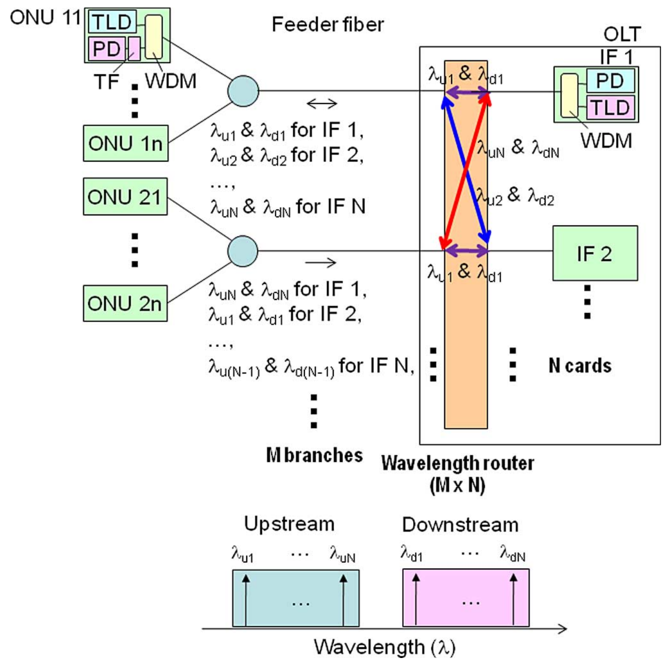

Fig. 3. Example configuration of dynamic WDM/TDMA-PON system.

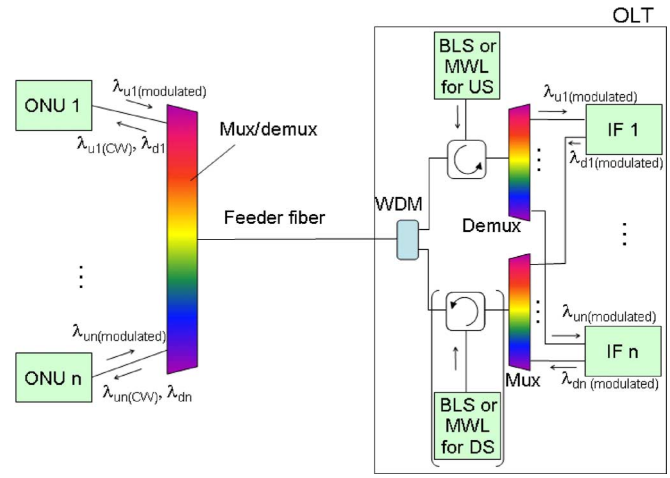

Fig. 4. Typical wavelength seeding and injection-locking schemes for realizing colorless ONUs.

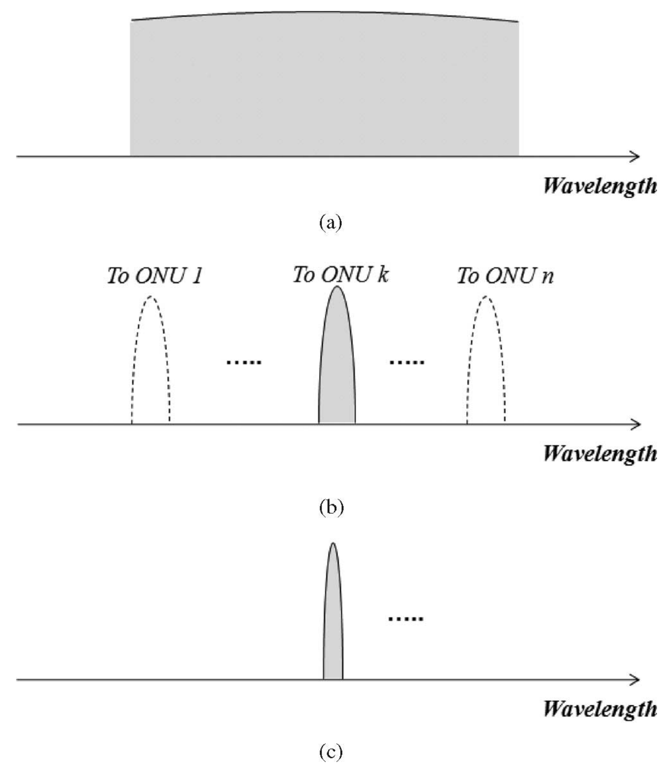

Fig. 5. Illustration of optical spectra at (a) BLS output, (b) mux/demux output to ONU k, and (c) ONU-k output, respectively.

Dynamic wavelength re-assignment adds some interesting features to PON. First, it permits each ONU to access an uncrowded IF (and the network behind the IF) when congestion occurs, i.e., load balancing among plural IF cards. Second, it allows each ONU to access a live/healthy IF (and the network behind the IF) when failure occurs, i.e., it provides resilience. Third, some of the IF cards may be turned off when the total traffic is low, a useful power-saving function.

III. Enabling Technologies for WDM-PON

This section reviews enabling technologies for the WDM-PON explained in Section II-A.

A. Colorless ONU Technologies

The simplest way of realizing the WDM-PON explained in Section II-A is to employ a different laser locked to a specific wavelength in each ONU. However, this greatly increases the burden of network operation and maintenance. Therefore, many researchers have been focusing on how to realize the 'colorless' ONU, i.e., a wavelength-independent ONU. The candidate schemes include injection locking [11], [12], wavelength seeding [13], [14], remote modulation [15], [16], spectrum slicing [17], [18], and wavelength tuning [19], [20].

1) Injection-Locking and Wavelength Seeding Schemes: Fig. 4 shows the typical configuration of WDM-PON systems that use either the injection-locking or wavelength-seeding scheme. A broadband light source (BLS) or a multiwavelength light source (MWL) is employed in the OLT as the centralized light source for the upstream (US) signals of all ONUs (ONU 1 to n in Fig. 4). Fig. 5 illustrates the optical spectra at BLS output, mux/demux output to ONU k, and ONU-k output for the case of using a BLS ($k = 1$ to n). As shown in Fig. 5(b), mux/demux slices the optical spectrum into n lightwaves: each lightwave is continuous wave (CW) having a different central wavelength, shown in Fig. 4 as "$\lambda_{uk(\mathrm{CW})}$."

In the injection-locking scheme, a Fabry–Perot laser diode (FP-LD) is used as the transmitter of each ONU. The sliced lightwave is injected into the FP-LD, so that the laser wavelength is locked to the wavelength of the injected lightwave. By directly modulating the FP-LD, each ONU can send an upstream signal with appropriate wavelength, "$\lambda_{uk(\mathrm{modulated})}$" in Fig. 4, which dispenses with the need for ONU-specific LDs. In the wavelength-seeding scheme, a reflective semiconductor optical

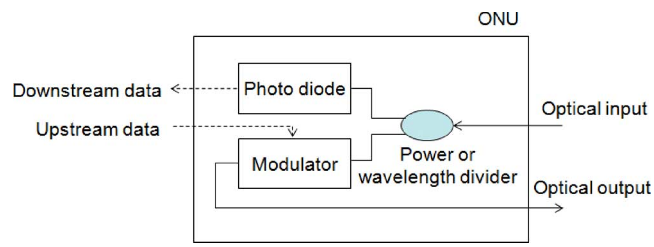

Fig. 6. Generic ONU configuration for WDM-PON with remote modulation scheme.

amplifier (R-SOA) is used as the transmitter of each ONU. The sliced lightwave is fed into the R-SOA, so that the lightwave is amplified and modulated by the upstream signal, and sent back to the mux/demux over the same fiber. The same scheme can be optionally applied to downstream signals by adding BLS or MWL to the downstream (DS) circuit; this yields colorless IF cards.

As described, the system configuration is almost the same for both schemes, but the physical mechanism used to generate the upstream signal is different. In both schemes, using MWL instead of BLS is an effective way of increasing the signal-to-noise ratio (SNR): 10-Gbit/s signal bit rate has been achieved by both schemes with the use of MWLs [21], [22]. Note that, the use of MWL requires a polarization-insensitive ONU transmitter unless polarization diversity is implemented in MWL, while BLS allows the use of simpler polarization-sensitive transmitter devices because it is an unpolarized light source.

In these schemes, the back reflected upstream signal in the fiber is mixed with the lightwave injected/supplied to the ONU. Assuming a reflection point close to the ONU, the relative power of the back reflection rises as the loss between the ONU and OLT increases. Thus, the amount of back reflection can determine the loss budget, i.e., the acceptable loss between ONUs and OLT [23]. Several attempts have been made to avoid this restriction and so increase the loss budget; examples include the use of frequency dithering [24], and the use of Manchester coding [25].

2) Remote Modulation Scheme: The remote modulation scheme employs an optical modulator as the transmitter in each ONU to realize the colorless ONUs, as shown in Fig. 6 [26]. Each ONU receives a continuous lightwave with a unique center wavelength, modulates it, and sends it as the upstream signal. An optical amplifier may be employed to amplify the lightwave before or after modulation. Fig. 6 shows a generic ONU configuration for a WDM-PON with the remote modulation scheme. Note that the wavelength-seeding scheme is sometimes categorized as a remote-modulation scheme [16], but it was described with the injection-locking scheme in this paper because of the system architecture attributes, as explained in Fig. 4.

The upstream and downstream signals can be allocated in different wavelength bands; a wavelength divider is used to divide these two bands and so to separate the downstream signal to the photodiode and the continuous lightwave (to be used for upstream transmission) in this case. Another interesting option is to reuse the downstream wavelength for upstream: a power

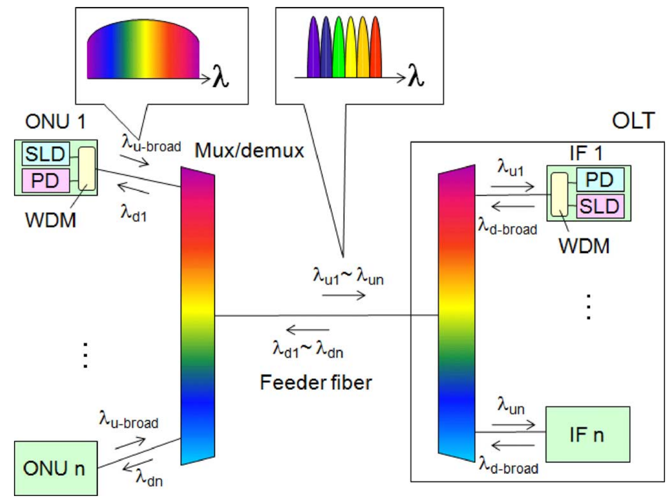

Fig. 7. Typical configuration of WDM-PON with the spectrum-slicing scheme.

divider is used instead of the wavelength divider in this case. Several ideas for the reuse of the downstream wavelength have been reported, such as the erasure of intensity modulation by SOA [27], and the use of phase modulation for downstream transmission [28].

3) Spectrum-Slicing Scheme: Fig. 7 shows a typical WDM-PON configuration with the spectrum-slicing scheme [29]. A super luminescent diode (SLD) or another device such as an optical amplifier is used as the transmitter in each ONU to generate a lightwave having a broad optical spectrum: the ONUs are colorless, i.e., all have SLDs that emit the same optical spectra. The lightwave is simply modulated with upstream data and sent to the OLT via two mux/demuxes as shown in Fig. 7. The optical spectrum from each ONU is sliced by the first mux/demux at different central wavelengths, and all upstream signals are thus WDM multiplexed in the feeder fiber as shown in the figure. The illustration is for upstream only, but this scheme can be optionally applied to downstream transmission to yield colorless IFs.

The signal-to-noise ratio (SNR) of the signal-signal beat noise can be expressed as being proportional to the ratio of the data rate to sliced bandwidth [17]. Therefore, to realize high-speed operation, the sliced bandwidth must be increased, which decreases the number of available channels assuming the light source has a fixed bandwidth. Increasing, i.e., broadening, the sliced bandwidth also results in a higher fiber-dispersion penalty. It has been reported that the use of forward error correction (FEC) is very effective in overcoming this drawback in that it increases not only the loss budget but also the spectrum efficiency [30]. The report confirmed that the use of FEC yielded 10-Gbit/s, eight-channel spectrum-sliced dense WDM (DWDM) transmission over a 20-km dispersion-shifted fiber (DSF) with the channel spacing of 200 GHz. It has been also successfully demonstrated that using an SOA is effective to suppress the intensity noise induced by the spectrum slicing in a WDM-PON with this scheme [31].

4) Wavelength Tuning Scheme: Employing a wavelength tunable laser in each ONU is the simplest way to unify the specification of all ONUs, i.e., to realize the colorless ONU. The key challenge is to realize a wavelength-tunable ONU that has reasonable cost for access network applications: several works have attempted to realize low-cost wavelength-tunable devices [19], [20]. In actual optical transmission systems for core networks, wavelength tunable lasers are becoming popular. For example, a wavelength-tunable transponder yields a unified transponder inventory for several wavelength channels. Further penetration and further cost reduction of tunable lasers in the core networks may allow their application to access networks.

B. Mux/Demux Devices

Another important item to research and develop for the WDM-PON is the mux/demux device. Because it is typically sited outdoors, its temperature and humidity tolerance must be much higher than similar devices in core networks. Also, it is desirable to make the mux/demux device completely passive because placing an active device outdoors greatly increases OPEX, and sometimes it is difficult to supply power to the device. From these viewpoints, athermal arrayed waveguide gratings (AWGs) [32] and thin-film-based WDM filters are reasonable candidates for WDM-PON applications. One interesting benefit of the AWG is that it provides feeder-fiber protection through its wavelength-routing characteristic. This means that it is not necessary to use either an optical coupler/splitter or an optical switch between ONUs and OLT for path protection [33].

IV. Enabling Technologies for Static WDM/TDM-PON

This section reviews enabling technologies for static WDM/TDM-PON detailed in Section II-B.

A. Loss-Budget Increase in General

The loss budget, i.e., the acceptable loss between ONUs and OLT in static WDM/TDM-PON systems, is typically much higher than that of simple WDM-PON systems because the splitter architecture is typically a combination of power splitter(s) and wavelength splitter/router(s) as described in Section II-B. In addition, as described in the same section, long-reach access is one of the attractive applications of static WDM/TDM-PON systems. Therefore, the loss budget increase is an issue that must be addressed.

The basic goal is to increase the ONU transmitter power and/or the receiver sensitivity: using optical post/preamplifiers is a direct way of realizing this, and the use of coherent detection has been studied as well to achieve very high receiver sensitivity [34]. The use of remotely pumped optical amplifiers is another approach to increase the loss budget, while keeping the path between ONUs and OLT passive [13].

Some studies have tackled the realization of long-reach, static WDM/TDM-PON systems in a cost-effective manner through the use of coarse WDM (CWDM) technologies in combination with wideband optical amplifiers [35]. A hybrid SOA and Raman amplification have been used to amplify CWDM signals [36].

B. Loss-Budget Increase of Colorless ONU Technologies

In order to simplify operation and maintenance activities, colorless ONU technologies are preferred for static WDM/TDM-PONs as well, especially if the number of required wavelengths is relatively high (e.g., 16 or more). However, the use of injection-locking, wavelength-seeding or remote modulation, makes it necessary to increase BLS/MLS output power to compensate the increased loss and to maintain the SNR, in addition to increasing the ONU output power. Furthermore, in the injection-locking and remote modulation schemes, the amount of back reflection in fiber limits the loss budget as described in Section III. Therefore, the ideas described in Section III that can suppress the degradation will be very important in static WDM/TDM-PON systems.

V. Enabling Technologies for Dynamic WDM/TDM-PON

This section reviews the enabling technologies for the dynamic WDM/TDM-PON detailed in Section II-C.

A. Tunable Transmitter and Receiver Technologies

The keys to realizing the dynamic WDM/TDM-PON systems described in Section II-C are to realize a wavelength-tunable transmitter as well as a wavelength selectable receiver, especially for the low-cost ONUs needed for access network applications. The following discusses the tuning/selecting speed of the transmitter and receiver. A fast tuning/selecting speed, e.g., several nanoseconds to several tens of nanoseconds, is quite attractive in terms of flexibly assigning both wavelength and time-slot resources in the same order as set by dynamic bandwidth assignment (DBA) in current TDMA-based PON systems. On the other hand, a slow tuning speed, e.g., several seconds, is still useful in terms of balancing the number of active/live ONUs per wavelength to provide fairness.

A wavelength tunable/selectable ONU with slow tuning/selecting speed can be considered as a candidate of the colorless ONU for WDM-PON and static WDM/TDM-PON systems as described in Sections II and III, respectively. Such a wavelength tunable/selectable ONU, based on the temperature control of a distributed feedback (DFB) laser, has been reported as a possible low-cost solution [18]. On the other hand, distributed Bragg reflector laser diodes (DBR-LDs), such as a sampled grating DBR-LD and a super structure grating DBR-LD (SSG-DBR-LD), are candidates for the fast tuning transmitter: a SSG-DBR-LD has been successfully used in a long-reach WDM-based PON field trial [37].

As for wavelength selectable filters, no viable candidate technology is known that can realize fast selection, while there are several technologies for slow selection, such as the thermally tuned semiconductor optical filter [38]. While a fixed-wavelength filter can be used if each ONU communicates with different IFs for upstream and downstream [10], the resulting system operation is more complex. Therefore, further research is needed to realize wavelength-tunable optical filters that offer fast selection.

It should be noted that each ONU has to employ a burst-mode receiver in this architecture, unlike traditional TDMA-based PON systems, which use such receivers only in the OLT side, because the downstream signals are not continuous due to the frequent change in wavelength. Therefore, decreasing the cost of burst-mode receivers is an important issue.

B. Mux/Demux Devices

AWGs are basically a mature technology for realizing the cyclic wavelength routing function explained in Section II-C. This wavelength routing function is becoming practical in core-network systems as the key function of optical routers.

C. Protocol and Algorithm for Dynamic Wavelength Assignment

In order to implement dynamic WDM/TDM-PON systems, the traditional TDMA-control protocol must be extended. Taking the protocol for GE-PON and 10 Gbit-EPON as an example, DBA is implemented by using REPORT frames and GATE frames; these are sent from/to each ONU individually. ONU sends REPORT frames to the OLT to demand the required bandwidth, and receives GATE frames that show when the ONU can send the upstream burst. The current GATE frame can carry time-slot information such as the start time and burst length to each ONU for the transmission of each upstream signal. It should be extended such that it can also carry the wavelength information.

Current TDMA-based PON systems depend on the effectiveness of the DBA algorithm. It determines the amount of bandwidth to be allocated to each ONU. A dynamic wavelength assignment (DWA) algorithm has been reported for dynamic WDM/TDM-PON systems that provide flexible bandwidth assignment [10]. Further studies to maximize fairness as well as efficiency are necessary to accommodate various system configurations as well as various deployment cases.

VI. Discussion on Future Directions

This section discusses future directions of practical PON systems based on the recent progress of WDM-PON and WDM/TDM-PON technologies described in the previous sections as well as the recent standardization activities on 10-Gbit/s TDM-based PON systems [4], [5].

The discussion considers how the whole access service network may evolve; the current access service network for consumers typically comprises a number of TDM-based PON systems and a layer-2 switch (L2 SW) to aggregate the data traffic and feed it to the core network. Fig. 8(a) shows an access service network based on 10-Gbit/s TDM-based PON systems with 32 ONUs that retains the current access service network configuration. An L2 SW with 10-Gbit/s interfaces is located to aggregate the traffic from many OLTs (128 OLTs, in the figure), so the access service network can handle data traffic from (to) 10^3–10^4 ONUs typically (4096, in the figure). An important point is that the TDM-based PON systems are used for not only sharing the feeder fiber but also providing a part of the aggregation function; this reduces the scale of aggregation needed in the L2 SW. This reduction results in lower power consumption, fewer interfaces and smaller L2SWs. DBA is done in each PON, and the priority control is done in PONs and L2 SW, to flexibly and fairly share the total bandwidth resources among the 10^3–10^4 ONUs.

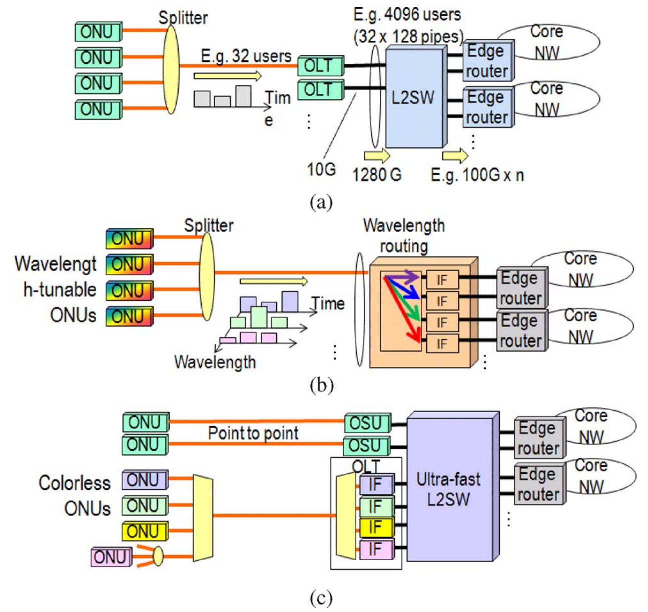

Fig. 8. Possible future access-service networks based on (a) 10-Gbit/s TDM-PONs with a 10 Gbit-interfaced L2 SW, (b) the dynamic WDM/TDM-PON system, and (c) point-to-point WDM-PON and/or static WDM/TDM-PON systems with an ultrafast L2 SW.

The following discusses two potential alternatives to this image from the functional viewpoint. One is to move (a part of) the aggregation function of L2 SW to PON systems. The other direction is its opposite, i.e., to consolidate the aggregation function into the L2 SW.

Fig. 8(b) illustrates a network configuration that follows the first direction with the use of the dynamic WDM/TDM-PON systems. By introducing wavelength-tunable transmitters in the ONUs as well as a wavelength router such as an arrayed waveguide grating (AWG) in the OLT side (a part of), the aggregation function of L2 SW can be moved to the PON part. This configuration increases the flexibility of bandwidth-resource allocation compared to Fig. 8(a) in that plural ONUs sharing the same splitter can enjoy maximum speed, i.e., 10 Gbit/s, simultaneously if the traffic of the other ONUs is not so heavy.

Fig. 8(c) illustrates a network configuration that follows the second direction with the use of point-to-point, WDM-PON and/or static WDM/TDM-PON systems. This configuration provides the same functionalities and the same performance as the former case, shown as Fig. 8(b). All resource allocation/control is done in the L2 SW. The optical access system(s) just provides fat pipes although some ONUs, e.g., those for a slower-speed service, may want to share the bandwidth via TDM/TDMA as shown at the bottom of Fig. 8(c).

The first direction may result in lower total scale and the power consumption of the access service network as it can reduce or eliminate the L2 SW. Its realization relies on further progress in the research and development of dynamic WDM/TDM-PON systems. Increasing the number of available wavelengths is also important for this application. The realization of the second direction relies on the further enhancement of L2 SW technologies, particularly the power saving function, in addition to WDM-PON and static WDM/TDM-PON technologies. Power saving will be the biggest hurdle for the ultrafast L2 SW because the number of L2 SW subscriber ports will be huge with this approach, e.g., 32 times that of the approach illustrated as Fig. 8(a). Integrating the huge number of connectors is another issue to be tackled. Further research and development activities on PON technologies as well as L2 SW technologies are encouraged, and the direction of practical systems will become clearer in the next few years.

VII. Summary

This paper reviewed the state-of-the-art technologies needed to realize flexible and scalable WDM-based PON systems after defining three architectures from the functional viewpoint. The three architectures are WDM-PON, static WDM/TDM-PON, and dynamic WDM/TDM-PON.

The main issue with the WDM-PON is how to realize colorless ONUs: five alternative schemes were introduced, and recent research was reviewed for each scheme. Next, studies/works on the realization of static WDM/TDM-PON systems were reviewed with the focus being placed on the loss-budget increase in general, as well as that expected with the use of colorless ONU technologies. Third, studies/works to realize dynamic WDM/TDM-PON systems were described: the technologies covered included wavelength-tunable transmitters and receivers, as well as higher layer considerations such as protocol extension and wavelength-assignment algorithms.

Last, future directions of practical PON systems were discussed based on the recent progress of WDM-PON and WDM/TDM-PON technologies. The paper closed with an expectation of further research and development activities on PON technologies to make the direction of practical PON systems clearer in the next few years.

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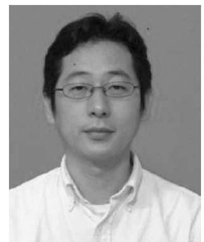

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