Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review [Invited]

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The passive optical network (PON) is an optical fiber based network architecture, which can provide much higher bandwidth in the access network compared to traditional copper-based networks. Incorporating wavelength-division multiplexing (WDM) in a PON allows one to support much higher bandwidth compared to the standard PON, which operates in the "single-wavelength mode" where one wavelength is used for upstream transmission and a separate one is used for downstream transmission. We present a comprehensive review of various aspects of WDM-PONs proposed in the literature. This includes enabling device technologies for WDM-PONs and network architectures, as well as the corresponding protocols and services that may be deployed on a WDM-PON. The WDM-PON will become a revolutionary and scalable broadband access technology that will provide high bandwidth to end users. © 2005 Optical Society of America

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1. Introduction

The *access network*, also known as the "*first-mile* network," connects the service provider central offices (COs) to businesses and residential subscribers. This network is also referred to in the literature as the *subscriber access network*, or the *local loop*. The bandwidth demand in the access network has been increasing rapidly over the past several years. Residential subscribers demand first-mile access solutions that have high bandwidth and offer media-rich services. Similarly, corporate users demand broadband infrastructure through which they can connect their local-area networks to the Internet backbone.

The predominant broadband access solutions deployed today are the digital subscriber line (DSL) and community antenna television (CATV) (cable TV) based networks. However, both of these technologies have limitations because they are based on infrastructure that was originally built for carrying voice and analog TV signals, respectively; but their retrofitted versions to carry data are not optimal. Currently deployed blends of asymmetric DSL (ADSL) technologies provide 1.5 Mbits/s of downstream bandwidth and 128 Kbits/s of upstream bandwidth at best. Moreover, the distance of any DSL subscriber to a CO must be less than 18000 ft because of signal distortions. Although variations of DSL such as very-high-bit-rate DSL (VDSL), which can support up to 50 Mbits/s of downstream bandwidth, are gradually emerging, these technologies have much more severe distance limitations. For example, the maximum distance over which VDSL can be supported is limited to 1500 ft. CATV networks provide Internet services by dedicating some radio frequency (RF) channels in a coaxial cable for data. However, CATV networks are mainly built for delivering broadcast services, so they don't fit well for the bidirectional communication model of a data network. At high load, the network's performance is usually frustrating to end users.

Passive optical networks (PONs) have evolved to provide much higher bandwidth in the access network. A PON is a point-to-multipoint optical network, where an optical line terminal (OLT) at the CO is connected to many optical network units (ONUs) at remote nodes through one or multiple 1:N optical splitters. The network between the OLT and the ONU is passive, i.e., it does not require any power supply.

PONs use a single wavelength in each of the two directions—downstream (CO to end users) and upstream (end users to CO)—and the wavelengths are multiplexed on the same fiber through coarse WDM (CWDM). For example, the Ethernet PON (EPON) uses 1490 nm wavelength for downstream traffic and the 1310 nm wavelength for upstream traffic. Thus, the bandwidth available in a single wavelength is shared amongst all end users. Such a solution was envisaged primarily to keep the cost of the access network low and economically feasible for subscribers. Various blends of the PON have emerged in recent years: the Ethernet PON (EPON) is a relatively recent version that is standardized in the IEEE 802.3ah [1], the broadband PON (BPON) is standardized in the ITU-T G.983, and the generic framing procedure based PON (GFP PON) is standardized in the ITU-T G.984.

An enhancement of the PON supports an additional downstream wavelength, which may be used to carry video and CATV services separately. Many telecom operators are considering to deploy PONs using a fiber-to-the-x (FTTx) model (where x = building (B), curb (C), home (H), premises (P), etc.) to support converged Internet protocol (IP) video, voice, and data services—defined as "triple play"—at a cheaper subscription cost than the cumulative of the above services deployed separately. PONs are in the initial stages of deployment in many parts of the world.

Although the PON provides higher bandwidth than traditional copper-based access networks, there exists the need for further increasing the bandwidth of the PON by employing wavelength-division multiplexing (WDM) so that multiple wavelengths may be supported in either or both upstream and downstream directions. Such a PON is known as a

WDM-PON. Interestingly, architectures for WDM-PONs have been proposed as early as the mid-1990s. However, these ideas have not been commercialized yet for many reasons: lack of an available market requiring high bandwidth, immature device technologies, and a lack of suitable network protocols and software to support the architecture. We believe that many of the above factors have been mitigated over the years, and WDM-PONs will soon be viable for commercial deployment. Hence, in this paper, we conduct the first comprehensive review of WDM-PON technologies: devices, architectures, and protocols that have been proposed by the research community over the past several years. We believe that this review should be valuable to a wide audience consisting of researchers, engineers, and executives who are interested in WDM-PONs.

This paper is organized as follows. Section 2 briefly describes the overall idea of a generic WDM-PON solution by using a simple example. Section 3 describes the device technologies suitable for WDM-PON. Section 4 reviews various WDM-PON architectures. Section 5 outlines some representative network protocols to support WDM-PONs. Section 6 discusses various services that may be supported on the WDM-PON. Section 7 concludes the paper.

2. Simple WDM-PON Architecture

Traditional single-wavelength PONs (henceforth referred to as the time-division multiplexed PON (TDM-PON)) combine the high capacity provided by optical fiber with the low installation and maintenance cost of a passive infrastructure. The optical carrier is shared by means of a passive splitter among all the subscribers. As a consequence, the number of ONUs is limited because of the splitter attenuation and the working bit rate of the transceivers in the central office (CO) and in the ONUs. Current specifications allow for 32 ONUs at a maximum distance of 20 km from the OLT and 64 ONUs at a maximum distance of 10 km from the OLT. A WDM-PON solution provides scalability because it can support multiple wavelengths over the same fiber infrastructure, is inherently transparent to the channel bit rate, and it does not suffer power-splitting losses, as will be explained below.

The straightforward approach to build a WDM-PON is to employ a separate wavelength channel from the OLT to each ONU, for each of the upstream and downstream directions, as shown in Fig. 1. This approach creates a point-to-point link between the CO and each ONU, which differs from the point-to-multipoint topology of the regular PON (TDM-PON). In the WDM-PON of Fig. 1, each ONU can operate at a rate up to the full bit rate of a wavelength channel. Moreover, different wavelengths may be operated at different bit rates, if necessary; hence, different varieties of services may be supported over the same network. In other words, different sets of wavelengths may be used to support different independent PON subnetworks, all operating over the same fiber infrastructure.

In the downstream direction of the WDM-PON (Fig. 1), the wavelength channels are routed from the OLT to the ONUs by a passive arrayed waveguide grating (AWG) router, which is deployed at a *"remote node"* (RN), which is where the passive splitter used to be in a TDM-PON. The AWG is a passive optical device with the special property of *periodicity*, which is the cyclic nature by which multiple spectral orders are routed to the same output port from an input port. This allows for spatial reuse of the wavelength channels. A multiwavelength source at the OLT is used for transmitting multiple wavelengths to the various ONUs.

For the upstream direction, the OLT employs a WDM demultiplexer along with a receiver array for receiving the upstream signals. Each ONU is equipped with a transmitter and receiver for receiving and transmitting on its respective wavelengths. In this example, the downstream and upstream transmissions occur in different wavelength windows, and these windows are separated using coarse WDM (CWDM). Within each window, the wavelengths are further separated using dense WDM (WDM).

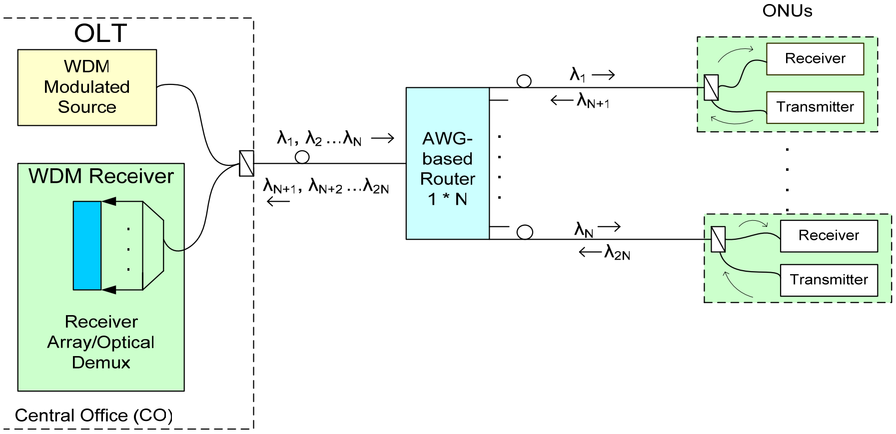

Fig. 1. Simple WDM-PON architecture.

A WDM-PON requirement is that it should be scalable in bandwidth as well as in the number of users. To satisfy this requirement, the optical devices that are needed for the architecture should be economically feasible. Enabling technologies along with device characteristics are discussed in the following section.

3. WDM-PON Device Characteristics and Options

A WDM-PON designer must decide on the appropriate wavelengths and their spacing, based on which the selection of devices may differ significantly. Subsection 3.A describes the two major wavelength options—coarse WDM (CWDM) PON and dense WDM (DWDM) PON. The OLT and ONUs have optical transmitters, receivers, multiplexers, and demultiplexers. Several WDM-PON transmitter options have been proposed, and they are summarized in Subsection 3.B. Receiver options, which are dependent on both loss and protocols, are explained in Subsection 3.C. Finally, various multiplexers and demultiplexers to be deployed at remote nodes (RNs) are shown in Subsection 3.D.

3.A. Wavelength Options

Wavelength spacing of more than 20 nm is generally called coarse WDM (CWDM). Optical interfaces, which have been standardized for CWDM, can be found in ITU G.695, while the spectral grid for CWDM is defined in ITU G.694.2. If the complete wavelength range of 1271 nm to 1611 nm, as defined in ITU G.694.2, is used with 20 nm spacing, then a total 18 CWDM channels are available, as can be seen in Fig. 2 [2]. A low-water-peak fiber defined in ITU G.652 C & D, which eliminates power attenuation in the 1370–1410 nm range seen in a normal single-mode fiber, can be used for this wide spectrum of transmission. The dispersion parameter in Fig. 2 indicates signal broadening, and this factor may limit the transmission distance as the data rate becomes higher.

Since strict tuning of wavelengths is not needed for the CWDM-PON, a thermal control part, called a thermo- electric cooler (TEC), is not required, making it cheaper than the DWDM-PON. Furthermore, the wavelength multiplexer with low channel crosstalk can be implemented easily for CWDM. It has been argued that the total system cost is 40% cheaper for the CWDM-PON [3].

The primary disadvantage of CWDM is that the number of channels is limited; therefore, the CWDM-PON lacks in scalability, especially when a normal single-mode fiber with water-peak attenuation range is used. Another disadvantage is that the shorter wavelength channels experience higher loss (see Fig. 2), thereby limiting the transmission distance or splitting ratio.

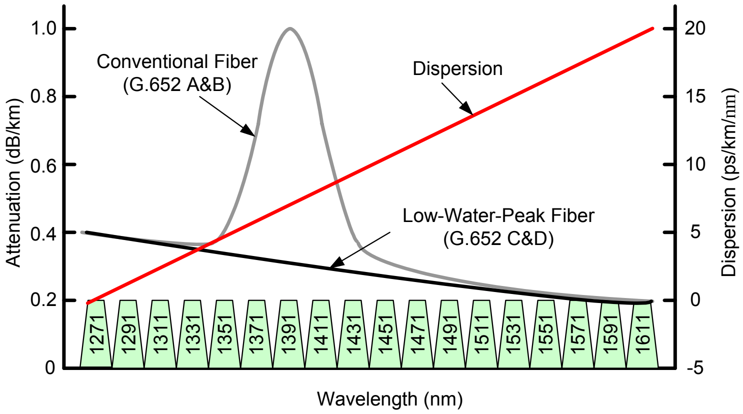

Fig. 2. Wavelength assignment for CWDM [2].

A brief example of the CWDM-PON can be found in the so-called "*triple-play*" PON service [4], where the 1550 nm wavelength channel is used for optional video CATV, the 1490 nm wavelength channel is used for downstream voice and data, while the 131 nm wavelength channel is used for upstream transmission [3]. An expanded application adopts 1360–1480 nm CWDM channels for premium business services, while usual triple-play services are provided to normal subscribers [3].

Dense WDM (DWDM) has wavelength spacing that is far lesser than that of CWDM, typically less than 3.2 nm, because DWDM has been developed to transmit many wavelengths in a limited spectrum region where an erbium-doped fiber amplifier (EDFA) can be used. A DWDM-PON is expected to be very useful for providing enough bandwidth to many subscribers, and it is regarded as the ultimate PON system. ITU G.692 defines a laser grid for point-to-point WDM systems based on 100 GHz wavelength spacing with a center wavelength of $193.1\,\mathrm{THz}(1553.52\,\mathrm{nm})$ over the frequency region of $196.1\,\mathrm{THz}(1528.77\,\mathrm{nm})$ to $191.7\,\mathrm{THz}(1563.86\,\mathrm{nm})$. This 100 GHz spacing has been applied to many DWDM systems. But 50 GHz spaced laser diodes (LDs) and filters are commercially available today, and they can be used to increase the number of channels. Also, wavelengths reaching up to 1600 nm have been used to exploit the cyclic property of the AWG, by having just one AWG at a remote node for demultiplexing and multiplexing in downstream and upstream directions, respectively. In a DWDM-PON, the wavelength of each optical source and the center wavelength of the WDM filter should be monitored and controlled carefully to avoid crosstalk between adjacent channels. Therefore, the DWDM-PON costs more than the CWDM-PON in field deployment since it needs wavelength-tuned devices and temperature control.

3.B. Transmitter Options

Optical sources are classified into four groups in this paper, depending on the way wavelengths are generated. These are (1) a wavelength-specified source, (2) a multiple-wavelength source, (3) a wavelength-selection-free source, and (4) a shared source. The multiple-wavelength source is applicable only to the OLT, the shared source is applicable to the ONU, and the remaining two are applicable to both.

3.B.1. Wavelength-Specified Source

This optical source emits a fixed wavelength from each component. A wavelength-monitoring circuit and a controller for each component are usually needed to tune the source to a required wavelength. A common distributed feedback (DFB) / distributed Bragg reflector (DBR) laser diode, a vertical-cavity surface-emitting laser (VCSEL) diode, and a tunable-laser diode can be categorized into this group.

Distributed Feedback (DFB) Laser Diode (LD): As a most common scheme for obtaining a single optical longitudinal mode, distributed Bragg gratings are etched inside the cavity of a DFB LD, which allows only the wavelength-matching gratings to be lasing [5]. If the grating is outside the cavity, it is called a distributed Bragg reflector (DBR) LD. Since there may occur a wavelength shift of $\sim 0.1\,\text{nm}/°\text{C}$, these LDs usually require a thermoelectric cooler (TEC) for stable operation as a WDM source. In addition, a wavelength locker, which helps the LD to lock exactly to its assigned wavelength, is needed. The DFB LD can be modulated directly for a WDM-PON deployment, where the distance is often less than 20 km. And it has good high-speed modulation property because of its narrow linewidth of less than a few MHz. In spite of all these advantages, the DFB LD is regarded as a costly way to implement a WDM-PON because a number of DFB LDs would usually be required, and each of them should be managed separately.

Vertical-Cavity Surface-Emitting Laser (VCSEL) Diodes: VCSEL has the potential for low-cost mass production since the entire cavity can be grown with one-step epitaxy on a GaAs substrate, which makes manufacturing and testing easy [6]. VCSELs with 850 nm and 1310 nm wavelengths are commercially available and widely used for LAN applications. But the VCSEL at 1550 nm wavelength is at its early stage of development because of poor optical and thermal properties of the laser material. Although it cannot be used as a WDM-PON source today, it can be adopted as an upstream source in a composite PON (CPON), described in Section 4.A. If this source in the 1550 nm DWDM range becomes stable and cheap, it will be a strong candidate for potential integration with other electronics.

Tunable Lasers: To keep in the inventory all different wavelength lasers needed for each channel of a WDM-PON and to install different lasers at each home is costly and not easy to maintain. In this sense, the tunable laser is attractive if it can be used for several WDM channels. The following types of principles are provided.

A mechanical-type laser, also called an external-cavity laser, is implemented by external grating or Fabry–Perot (FP) cavity, which is controlled mechanically. Because of its wide tuning range of up to 500 nm and good wavelength accuracy, it can be used for instrumentation purpose. However, the external-cavity tunable laser requires an external modulator for high-speed modulation because of its long cavity length. Also, the lack of long-term stability hinders the tunable laser's application for telecommunications.

A thermally tunable DFB uses the wavelength-shift property of the DFB LD because of its cavity-index change with temperature. With the aid of optimized thermal design and temperature controllability over a wide range, the wavelength change of the thermally tunable DFB reaches up to 4 nm [7]. This LD's tuning time is long, sometimes up to a few seconds. Thus, this type of LD is not good for an architecture where fast switching is required. However, this LD can be useful for WDM-PON transmitters with fixed wavelength.

Based on this scheme, commercial tunable products over multiple (e.g., eight) adjacent ITU DWDM channels have appeared [8, 9]. This eliminates the need to reserve all different wavelengths of DFB LDs for each WDM-PON transmitter.

The tuning time of the DFB/DBR LD is reduced effectively by adjusting the injection current into one or more sections of the LD cavity. Injected carriers change the effective refractive index within the optical cavity, leading to a wavelength change. The tuning time is of the order of nanoseconds, which is the fastest known thus far. Since the maximum index change is about 1%, the maximum tuning range in the wavelength region of our interest is about 10–15 nm [12]. The drawback of this laser is that it is susceptible to mode hopping and mode competition [13] because of multiple electrodes on a laser cavity required for current injection, which degrades the transmission performance [5, 12].

3.B.2. Multiple-Wavelength Source

Individual-wavelength-specified sources are not convenient for use in the OLT of a WDM-PON, because they require many optical sources set to their own wavelengths. If a component generates multiple wavelengths at the same time, it will be very useful for the OLT. Several WDM channels, integrated in a compact device, can be tuned simultaneously. Three types of such multiple sources, which have been proposed in the literature, are described below.

Multifrequency Laser (MFL): An AWG and amplifier arrays are integrated in this device for wavelength selection and its amplification, respectively, as shown in Fig. 3 [13, 14]. Mirrors on cleaved facets define an optical cavity of the laser-diode modules. If the AWG is tuned, it changes whole output wavelengths. A device integrating 18 WDM channels was implemented using this scheme [15]. It can also be used as a tunable LD by turning on each amplifier. Although direct modulation is possible with this device, there is a modulation-rate limit because of its long laser cavity.

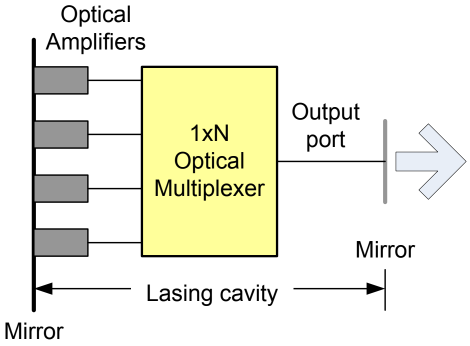

Fig. 3. Structure of a multifrequency laser [14].

Gain-Coupled DFB LD Array: Another possible way of integrating multiple wavelength sources is to implement DFB LD arrays by combining a gain-coupling mechanism and a tuning capability in one LD module [16]. Thin-film resistors are integrated for tuning wavelengths by controlling the temperature. The advantages are compact size and high-speed modulation. But it is difficult to accurately maintain every channel at the correct wavelength, since each lasing wavelength is determined by an independent filter. Considering that different types of gratings are etched inside a chip, this scheme is more realizable for a small number of channels.

Chirped-Pulse WDM: Source A short-pulse generator followed by a roll of fiber can work as a WDM source, as illustrated in Fig. 4 [17]. A 100 fs Gaussian pulse from a mode-locked erbium fiber laser provides 4.4 THz spectral bandwidth, enough for 44 WDM channels at 100 GHz spacing. A fiber roll provides fiber dispersion to this pulse, which broadens it temporally. If this pulse is modulated and then is provided to a following WDM splitter, different channels carrying their own information will come out of different ports. Since each generated pulse is divided into all ONU channels, the number of channels is limited by the ratio of the data-modulation frequency to the repetition rate of the laser. Therefore, this method is better for applications where data rates in each channel are rather low (or modest), but many WDM channels are required. The problems of aligning pulse width, temporal width, and WDM free spectral range (FSR) may be the difficulties that should be solved before the commercial viability of this solution.

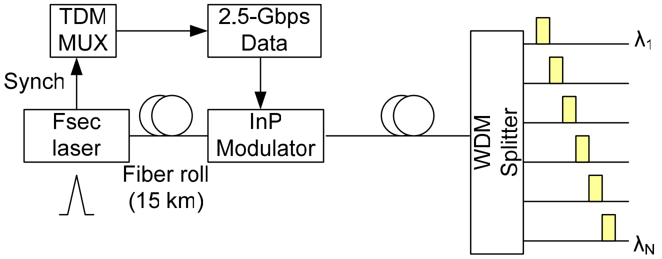

Fig. 4. Chirped-pulse WDM source for the OLT [17].

3.B.3. Wavelength-Selection-Free Source

In this type of source, the wavelength is decided not by itself, but by external factors such as a filter or injection signal. Sometimes, the wavelength of the source drifts with the ambient temperature, aging effect, or circuit malfunction. The management of each ONU, whose wavelength is unique in a PON group, is not easy because of the difficulty of finding its exact reference wavelength. A wavelength-selection-free source can help such sources to operate free from the wavelength-tuning problem because the wavelengths are determined less by the environmentally sensitive external factors such as optical filters or injected signals.

Spectrum-Sliced Source: By slicing the spectrum of a broadband optical source with a narrowband optical filter, a unique wavelength for each WDM channel is achieved. Several combinations of broadband optical source and filter have been tried. For example, the super-luminescent light emitting diode (LED) [18], EDFA [19, 20] and FP LD [21] have been used for optical sources, while AWG and FP filters have been used for optical filters. Since only a narrow spectrum part of the original source is used, this source usually lacks power, requiring an optical amplifier. This method also has a limitation on the modulation speed because of several sources of noise such as mode-partition noise, intensity noise, and optical beat noise, which are inherent properties of multimode or broadband sources.

Injection-Locked Laser: A multimode laser, such as FP LD, has the property that it excites only one mode when a well-adjusted external optical signal is coming in [22]. Careful control of the modulation index, laser bias current, and power of the external optical excitation are required to increase the efficiency of the locking [23]. FP LDs locked to externally injected, spectrum-sliced broadband light sources (BLS) were field tested for commercial use, as shown in Fig. 5 [24]. Antireflection coating on the front facet of the laser is added to increase the injection efficiency. Cavity length is increased to have at least one lasing mode within the bandwidth of the injected amplified spontaneous emission (ASE). This method generates 32 WDM channels at the same time. A maximum power difference of 7 dB was reported among channels as the injected wavelength deviated from the lasing wavelength or from the envelope peak of the FP LD. It is difficulty to increase the data rate but this laser shows better performance than the spectrum-sliced multimode source.

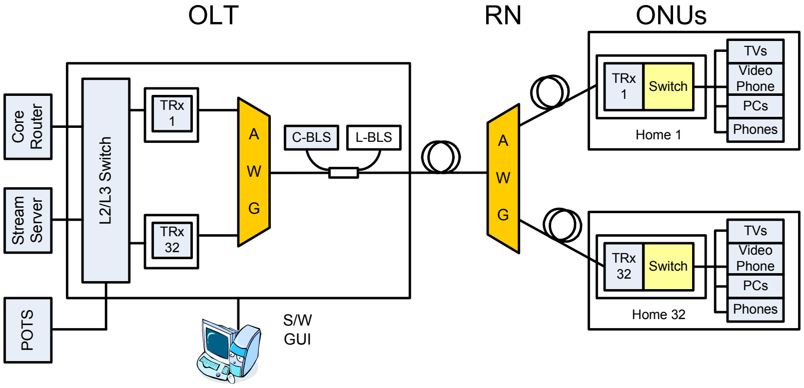

Fig. 5. Field trial of a WDM-PON based on injection-locked LD scheme [24].

3.B.4. Shared Source (or Loop-Back Source) for ONU

Some researchers have tried to eliminate optical sources at the ONU, because it is risky and costly to let each ONU manage the ONU's transmission wavelength. If one of them deviates from the assigned wavelength, the deviated channel may degrade not only itself but also its adjacent channels. As a solution, all optical sources are proposed to be provided from the OLT, and the ONU just modulates the provided unmodulated optical source. Sometimes, even one wavelength channel can be used in both directions, leading to the so-called shared-source solution, by modulating only a partial temporal region for downstream and leaving unmodulated the remaining region for upstream. Two types of modulator—external modulator and semiconductor optical amplifier (SOA)—have been used for this purpose.

When the downstream optical signal is split at the ONU and part of it is provided to an external modulator, then this signal can be modulated at high speed for upstream transmission. One proposal uses a tunable laser at the OLT, which can reach each ONU in turn by changing the wavelength of the LD [25]. Only half of the time is spent on downstream data and the other half on upstream using the external modulator. When the ONU is operated in this way, the power margin and the polarization, i.e., the direction of the electric field that varies randomly in normal optical fiber, of the optical signal must be considered, because the shared source would experience a round-trip signal loss and the output of an external modulator usually varies with the input signal's polarization. At the same time, the cost of the modulator at each ONU may be an obstacle to its practical use.

A reflective-type SOA, which can compensate for the round-trip signal loss, has been proposed for use as a shared source, as shown in Fig. 6 [26]. The unpolarized spectrum-sliced ASE source provided to the ONU is amplified and modulated by the SOA and reflected back to the OLT. The cost of the SOA still remains as the problem to solve before commercialization.

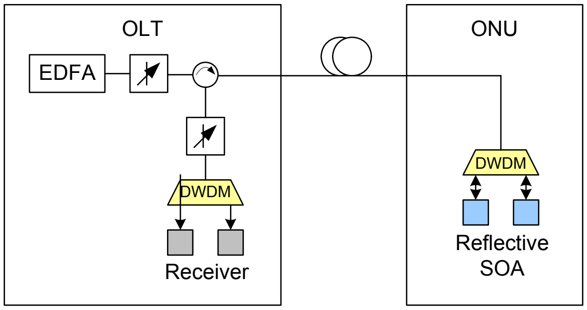

Fig. 6. Shared source using a reflective SOA [26].

3.C. Receiver Options

A receiver module consists of a photodetector (PD) and its accompanying electronics for signal recovery. Common PDs are positive-intrinsic-negative (PIN) and avalanche photodiode (APD), which find different applications according to the required sensitivity. Electronic parts, usually composed of preamplifier, main amplifier, and clock and data recovery circuits (CDRs), depend on the protocol used on each wavelength. Since each wavelength can work separately in a WDM-PON, each receiver can be configured differently.

3.C.1. Photodiodes

The power of the optical signal that reaches a receiver module is determined by its transmission distance and splitting ratio. If the WDM-PON is used in a multistage structure, the received power will become smaller. Therefore, caution should be paid to these sensitivity options. A PIN-type PD, so called because it is composed of P-doped, intrinsic, and N-doped semiconductors, is very common because of its simple structure, ease of use, and low cost. Its sensitivity, or the required optical power, is not good because it does not have any amplification procedure in itself. As transmission loss becomes larger and the received optical power does not satisfy the receiver sensitivity of the PIN PD, it should be replaced with an APD that has $\sim 10\,\text{dB}$ higher sensitivity at the cost of a higher price. The better performance originates from its internal amplification process called the avalanche effect. Various combinations of LDs and PDs may be taken into consideration. If a high-power OLT is used, then a cheap PIN PD can potentially be a better candidate at the ONU. But, for the upstream case, having a high-power source at each ONU may be quite costly. Therefore, to have an APD at the OLT with a low-power ONU can be a better solution.

3.C.2. Recovery Circuits

A WDM-PON is transparent to the protocols or signals, meaning that it can carry any kind of signal format. Various kinds of transmission protocol, such as EPON, BPON, Ethernet, SONET and others, can use a WDM-PON as their physical layer. But receivers at the OLT and the ONU should satisfy the specification required by the adopted protocol. If multiple ONUs of a WDM-PON share one wavelength using EPON's multipoint control protocol (MPCP), which makes each ONU transmit data in its assigned time slot, the OLT receiver must recover data from signals with different amplitudes and phases (so-called burst-mode signals) coming from several ONUs, as specified in IEEE 802.3ah, while normal constant-mode receiver circuits are used in each ONU because the downstream signal is continuous. But, in a WDM-PON, where each unique pair of OLT and ONU is connected by one wavelength, a burst-mode receiver is not needed anymore.

3.D. RN (Remote Node) Options

The remote node (RN) in a PON can be made of either a power splitter or a passive wavelength router. A power splitter distributes all incoming signals evenly into all output ports, requiring a wavelength filter at each ONU. Insertion loss, uniformity, return loss, and operating temperature are important features for its selection. The specifications of the splitter can be found in Telcordia GR1209 [27] or GR1221 [28]. Although the splitter is a simple, low-cost, distribution structure, it requires optical filters with different center wavelengths at ONUs. Also, more signal loss occurs with a splitter than with a wavelength router.

The AWG has been a successful device in WDM industry. It has been used in many long-distance WDM systems as a multiplexer/demultiplexer and as an add-drop multiplexer (ADM). It routes each specific wavelength to a unique output port, separating multiple wavelengths at the same time. Its cyclic wavelength property enables the AWG to be used at the RN, both as multiplexer and demultiplexer at the same time, as shown in Fig. 7. When the upstream transmitters use wavelengths that differ from the downstream in integral multiples of the free spectral range (FSR) of the AWG, the same AWG output port can be assigned for both upstream and downstream transmission, as can be seen in 7(a). For this purpose, a CWDM filter is used at the ONU for separating the two signals [29] But, if the upstream should use the same wavelength as the downstream, shared source for instance, then the two different output ports should be assigned to an ONU and a $2 \times N$ AWG must be used at the RN, as shown in Fig. 7(b).

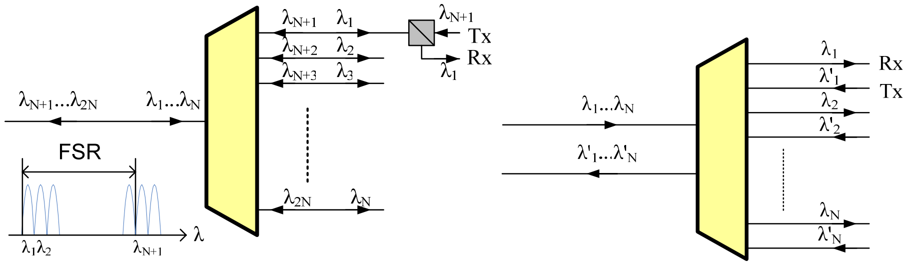

Fig. 7. RN based on the cyclic wavelength property of the AWG: (a) bidirectional transceiver at the ONU, and (b) unidirectional transceiver at the ONU.

The AWG's insertion loss of about 4–5 dB (regardless of the number of channels) is far less than that of the optical splitter, which has an excess loss of 0.5–1.5 dB in addition to the (large) $1{:}N$ splitting loss. But, in spite of all such good properties, the AWG's center wavelength shift of ~ 0.01 nm/°C makes it difficult to be used in the RN of a WDM-PON, since the RN is located in the harsh temperature environment such as from -40°C to $+$ 85°C. This temperature dependency originates from the index change of silica waveguide, which leads to a change in optical length of the circuit of the AWG. But recently, athermal packages of AWG have been reported, which are made by having a compensating material that has a different temperature coefficient than silicon in part of the AWG's lightwave circuit [30, 31].

There is another common scheme for multiplexing/demultiplexing wavelengths, called thin-film filters or multilayer interference filters. By positioning cascaded filters in the optical path, wavelengths can be demultiplexed, and vice versa. Each filter is designed to transmit a unique wavelength while reflecting others. This type of filter is better for CWDM while AWG is good for implementing large channel counts.

Recently, a new type of wavelength router, called a bulk grating, has been suggested for use in a DWDM system. This bulk grating is based on a bulk-type diffraction grating and is reported to have less insertion loss of sub-3 dB and to go to narrower channel spacing and larger channel counts compared to AWG, for instance, 160 channels with 25 GHz channel spacing [32]. But there remains a dispute on which is the better solution between AWG and bulk grating. The AWG has an apparent advantage of integration with other devices in thin structure since it is implemented on a silica-based planar lightwave circuit (PLC), while the bulk grating has a potential for temperature insensitivity and narrow channel spacing.

4. WDM-PON Architectures

Several WDM-PON architectures have been proposed for providing scalability that is lacking in traditional PONs. As previously mentioned and as described in Fig. 8, a straightforward approach to increase the capacity of a TDM-PON is to assign a separate wavelength channel to each user. However, this solution provides high performance at a high cost; e.g., whenever a user shuts down his connection, then the corresponding transceiver at the OLT is idle, and will not be able to support other users, in which case the network resource is left unused. In this section, we review some of the representative WDM-PON architectures which have been proposed in the literature.

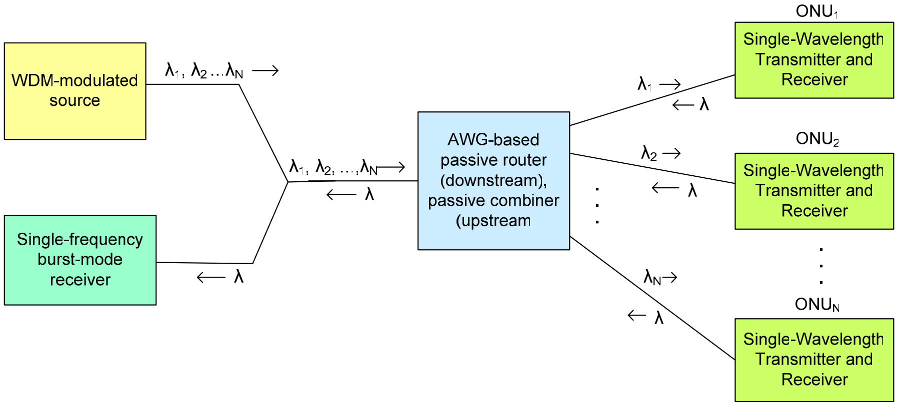

Fig. 8. Architecture of CPON [33–35].

4.A. Composite PON (CPON)

To solve the scalability limitation of traditional PONs, one of the earliest WDM-PON architecture proposals based on the AWG concept employed WDM in the 1550–nm band in the downstream direction and a single upstream wavelength in the 1300–nm band shared through time-division multiple access (TDMA). While an earlier design of this architecture used separate fibers for upstream and downstream [33, 34], an integrated type of device was proposed that performed WDM routing in one wavelength window and wavelength-independent power combining in a second window on a single fiber through CWDM. This architecture has been referred to as the composite PON (CPON) in the literature [35]. A single-wavelength, burst-mode receiver is used at the OLT to receive the upstream signal. A burst-mode receiver is required to synchronize to the clock signals of different transmitting ONUs, which may be at different distances from the OLT. Figure 8 shows the layout of a CPON.

CPON avoids the drawbacks of upstream WDM but is limited in the fact that a single-frequency laser, such as a distributed-feedback (DFB) laser diode (LD) at the ONU, may be economically prohibitive.

4.B. Local Access Router Network (LARNET)

The LARNET (local access router network) architecture [36] attempts to work around the limitation in CPON by employing a broad-spectrum source at the ONU, such as an inexpensive light-emitting diode (LED) whose spectrum is sliced by the AWG-based router into different optical bands in the upstream direction. The edge-emitting LED emits a broad spectrum of wavelengths centered around a single wavelength, as compared to the DFB laser, which emits only one wavelength of light. An advantage of using an edge-emitting LED is that each ONU can have the same device, as opposed to employing DFB lasers at each ONU, which may require for the DFBs to be different.

The LARNET architecture is shown in Fig. 9. One broad-spectrum source from each ONU is input to different ports of the AWG router. Depending on the input port, the wavelength component that is sliced at the output port is different. Therefore, at the output port, we observe many wavelength components, each corresponding to an input source from an ONU. The downstream signal with multiple wavelength components at the CO is generated by a multifrequency laser (MFL), which is coupled onto the transmission fiber through a 1.3 or 1.5µm multiplexer. A broadband receiver (unlike a single-wavelength burst-mode receiver employed in CPON) is also employed at the CO, which can receive any spectral component of the edge-emitting LED. In essence, the OLT at the CO can receive on any wavelength from any of the ONUs. Having a single receiver at the OLT requires that the upstream channel be shared between the ONUs using a scheme such as TDMA.

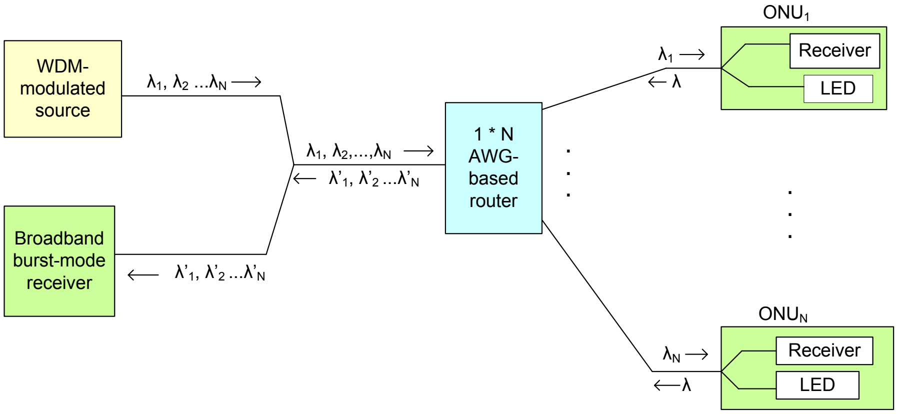

Fig. 9. Architecture of LARNET [36].

Edge-emitting LEDs are much cheaper compared to DFB lasers, so they reduce the cost of the ONU. The limitation with this architecture is that spectrally slicing a broad-spectrum source by an AWG may lead to high power loss. Therefore, the distance from the OLT to the ONU is considerably reduced in LARNET.

4.C. Remote Interrogation of Terminal Network (RITENET)

RITENET (remote interrogation of terminal network) [37] aims to avoid the transmitter at the ONU by modulating the downstream signal from the OLT and sending it back in the upstream direction. At the ONU, the light is split by a passive tap, with a portion of the light detected by the receiver. The remainder is looped back toward the CO through a modulator. The signal from the OLT is shared for downstream and upstream through time sharing. A $2 \times 2N$ AWG-based router is used to route the wavelengths.

At the CO, a tunable laser whose modes match with those of the AWG is wavelength stepped through the ONU channels. Thus, both the upstream and downstream channels have to be shared by the ONUs using TDMA or dynamic bandwidth allocation. Alternatively, as has been suggested in some recent architectures [38], an array of transmitters and receivers may be employed at the OLT. In this case, channel sharing is not required. Since the same optical channel is used for both upstream and downstream, they must be separated on two different fibers. Figure 10 shows the architecture of RITENET.

While RITENET helps in reducing end-terminal costs at the ONU, the distance from the OLT to the ONU is much less, as the signal at the OLT now has to travel double the distance. The number of fibers employed in the architecture is doubled, thus doubling the cost of deployment and maintenance. Also employing either a tunable laser or an array of transmitters and receivers at the OLT makes RITENET a more expensive architecture compared to CPON and LARNET. The architecture, however, has some advantages, such as the availability of symmetrical bandwidth in the downstream and upstream directions. Also, the upstream signal does not suffer the spectral-slicing loss seen in LARNET.

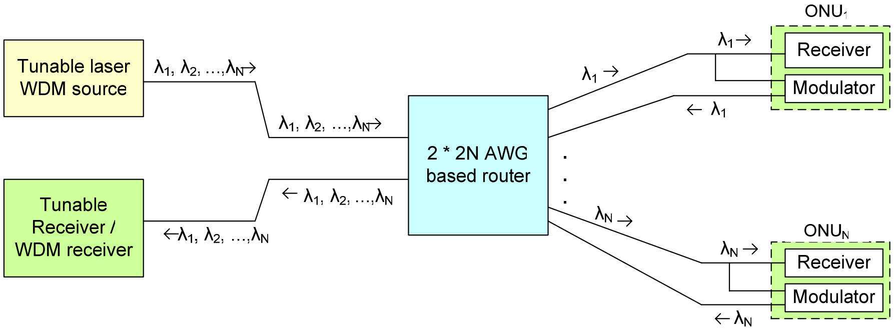

Fig. 10. Architecture of RITENET [37].

4.D. Multistage AWG-Based WDM-PON Architecture

The above architectures have two main limitations: (1) difficulty in scaling the number of ONUs once the network is laid out, and (2) limited number of users, because the fabrication technology limits the AWG size. To overcome these limitations, a multistage architecture was proposed in [39]. This architecture, which is referred to as a multistage WDM-PON, exploits the periodic routing property of the AWG so that the reuse of a given wavelength for more than one subscriber is possible. This architecture provides scalability in bandwidth as well as in number of users, either by employing additional wavelengths at the CO or by cascading multiple stages of AWGs with increasing AWG coarseness at each stage.

This architecture is shown in Fig. 11. It shows how additional AWGs may be deployed to scale from an 8-wavelength, 8-ONU WDM-PON architecture to a 32-wavelength, 32-ONU WDM-PON architecture. The subscript of the wavelength denotes the wavelength number, while the superscript denotes the source $\lambda_1{}^2$ (e.g., $\lambda_1{}^2$ denotes wavelength 1 from laser 2). This idea has several merits. The legacy ONUs—ONU_1 to ONU_8—remain unaffected and continue to use wavelengths $\lambda_1{}^1$ to $\lambda_4{}^1$ and $\lambda_1{}^2$ to $\lambda_4{}^2$. The legacy 2×8 channel AWG is maintained, and 8 new 1×4 channel AWGs are used to scale the network.

4.E. DWDM Super-PON (SPON) Architecture

A PON is limited in its transmission distance and the number of nodes it can support because of a limited power budget. For instance, the maximum transmission distance of EPON is 20 km and the maximum number of nodes it can support is 32. Several network operators are interested in extending the service range while bypassing local exchanges in order to significantly reduce operating costs [40]. The super-PON (SPON) proposal covers a range of over 100 km with a splitting ratio reaching 2000 with the aid of optical amplifiers (OAs) [41]. Optical amplifiers are placed in the long feeder and after the first splitting stage; thus this provides enough power budget to the system. The cost benefits stem not only from sharing resources, but also from consolidating switching sites. However, the single-wavelength SPON has a bandwidth limitation since a wavelength is shared by many ONUs.

A DWDM SPON is suggested to increase the bandwidth by providing several wavelengths in both directions [42]. The suggested architecture can be seen in Fig. 12. In this scheme, each 1 × N power splitter PON uses two DWDM channels, one for upstream and the other for downstream. The "blue" half (1525 nm–1543 nm) of the C-band carries downstream channels while the "red" half (1547 nm–1565 nm) carries upstream channels, which are separated by low-cost red or blue filters (RBF). The ONU uses a shared source (see Subsection 3.B.4). An electroabsorption modulator—semiconductor optical amplifier (EAM-SOA) can work as a colorless ONU that is used not only for modulation but also for amplification. The repeater site contains a continuous-wave (cw) seed laser followed by a booster amplifier, distributing an upstream optical source to each ONU within a splitter PON group. All upstream wavelengths are amplified by an EDFA preamplifier before being separated into each receiver at the OLT.

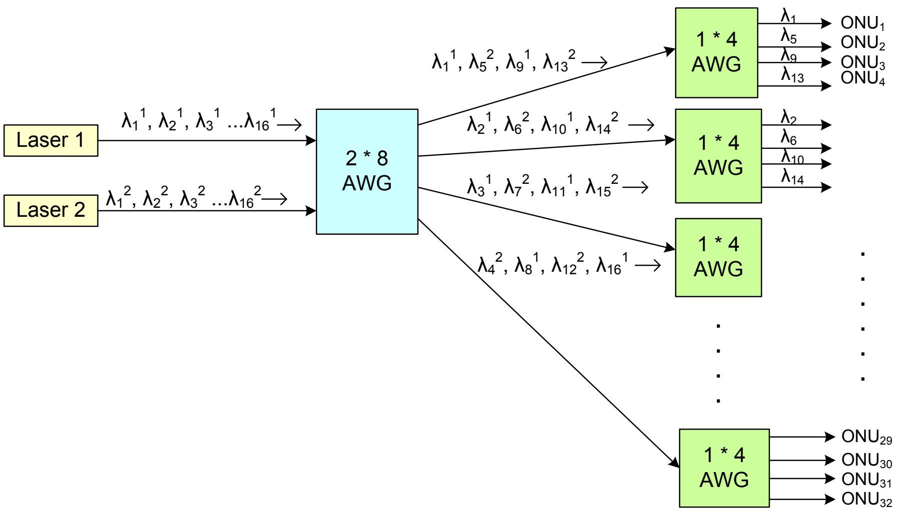

Fig. 11. Multistage AWG-based architecture [39].

While this SPON architecture makes long-distance service possible and accommodates many access nodes, it uses active parts such as optical amplifiers and seed sources in the middle of the deployment that requires electric power and therefore regular maintenance. Thus, it is not passive, which is the fundamental requirement of a PON. Therefore, this architecture should compete with other metro solutions with respect to cost and convenience of management.

4.F. SUCCESS-DWA PON Architecture

The Stanford University access dynamic wavelength assignment (SUCCESS-DWA) PON architecture [43] aims to offer scalability by employing dynamic wavelength allocation

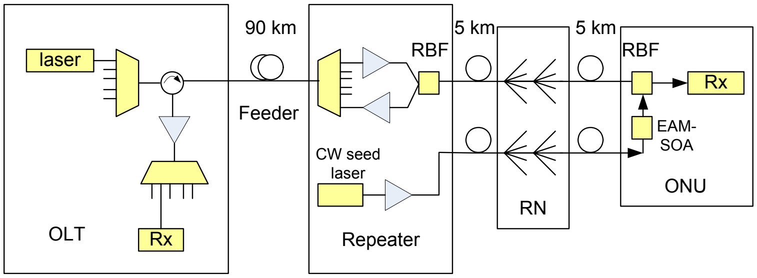

Fig. 12. DWDM super-PON (SPON) architecture using colorless ONUs [42].

(DWA) to provide bandwidth sharing across multiple physical PONs. This is done while the existing arbitrary field-deployed PON remains intact.

Figure 13 shows the network architecture of the SUCCESS-DWA PON. It employs tunable lasers (TLs) and the AWG at the CO, while WDM filters and a burst-mode receiver are employed within the ONUs. The upstream and downstream traffic is separated by a wideband WDM filter residing between the AWG and the PON. This architecture requires that all wavelengths from the OLT can reach all ONUs across separate physical PONs. TL_1 can reach PON_1 through AWG channels $\{1, 5, 9, \ldots\}$; it can also reach PON_2 through channels $\{2, 6, 10\ldots\}$, and likewise for PON_3 and PON_4. So, a TL can communicate with any user on a particular PON by determining what wavelength falls in the passband of the user and what wavelength exits the AWG toward that particular PON. The architecture provides scalability by initially deploying one TL and one AWG in the CO, which services multiple subscribers across several PONs. As the demand grows, the architecture can be scaled by adding more TLs to the AWG or by adding another AWG along with more TLs, as shown with the dotted AWG in Fig. 13.

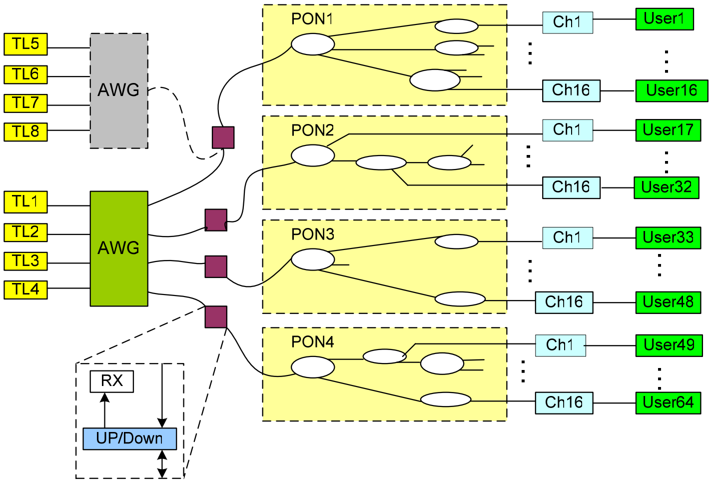

Fig. 13. SUCCESS-DWA PON architecture [43].

The SUCCESS-DWA PON requires an appropriate scheduling algorithm, since at most one TL can access any user at any given time, and the TL is a shared resource since the number of TLs is typically less than the number of users. The scheduler must maintain fairness, avoid collision, and maximize the use of the TLs. One approach employs several virtual output queues to avoid head-of-line blocking, and a longest-first queueing scheme or any other sophisticated scheme can be used to determine the order in which to service the queues. A suitable arbiter is needed to prevent two TLs from accessing the same queue simultaneously, since any queue can be serviced by many TLs. This approach inherently avoids collision but is limited in scalability for a large number of users. Another approach employs queuing at the transmitters. The incoming packets are assigned to the transmitter with the shortest queue to minimize delay. To ensure that no two packets head to the same end-user overlap across different queues, the scheduler can keep track of the destinations of the last packet in the queues and assign the incoming packet to the TL queue if they have the same destination. Quality of service (QoS) can be achieved by prioritizing the packets when assigning them to the queues.

The important features of the above-mentioned architectures are summarized and compared in Table 1.

Table 1. Comparison of Various WDM-PON Architectures

		CPON [33]	LARNET [36]	RITENET [37]	Multi-Stage [39]	Super-PON [42]	Success-DWA [43]
Main Objective of architecture		AWG based basic system	Reduce ONU Cost	Reduce ONU Cost	Scalable PON Wide-area service	Long-distance Wide-area service	Scalable PON Throughput increment
Sharing of Fiber		Up/down shared or separate	Up/down shared	Up/down separate	Dependent on upstream option	Up/down shared	Up/down shared
Sharing of Wave-length	down	1 λ/ONU	1 λ/ONU	Up/down shared (TDMA, dynamic allocation)	Dependent on upstream option	Share (TDMA)	- Shared among ONUs - Up/down shared (TDMA, dynamic allocation)
	up	Shared (TDMA)	Shared (TDMA, CSMA/CD)			Share (TDMA)	
Scalability		Poor	Poor	Poor	Good	Good	Excellent
Cost of user terminal (ONU)		Poor (DFB LD)	Good (LED)	Good	Dependent on upstream option	Poor	Poor
Cost of deployment		Good	Good	Poor	Very poor	Good	Poor
Distance (OLT-ONU)		Average	Poor	Very poor	Average	Excellent (~100 Km)	Average

5. Protocols for WDM-PONS

In WDM-PON, one of the important functions for high efficiency and high functionality is intelligent control including service-level agreements (SLAs). The intelligent control functions are composed of resource allocation among users, QoS control between multiple services and users, connection control including multicasting, and access authority control for secure access and fault control. Recently, studies on control protocols for WDM-PON have begun, and wavelength- or bandwidth-management protocols have been proposed as the first step.

If each channel of the WDM-PON works independent of the others, then the WDM-PON system may not need an additional medium-access control (MAC) protocol. For example, if a wavelength is assigned for an EPON group, then only the MAC protocol of the EPON system is used since this wavelength does not have any interaction with other channels. This is a practical and simple approach in the initial stage of WDM-PON implementation, and this protocol-transparency property is regarded as one of the merits of the WDM-PON. But this scheme may not utilize bandwidth efficiently, especially when some wavelengths are overloaded while others have a light load. If wavelengths are shared among ONUs, then the total throughput may be increased significantly. For this purpose, a new wavelength control protocol, or WDM-PON protocol, which helps to set up communication among the OLT and the ONUs, is needed. It will control tunable LDs and WDM filters. In addition to the basic communication protocol, a new dynamic bandwidth assignment (DBA) algorithm that assigns not only time slots but also wavelengths to each OLT and ONU is also needed. The protocols and algorithms for the WDM-PON are in their initial stage of study because they are dependent on the architecture, which is still in the early phase of study. While various types of architectures have been proposed, no specific one is dominant. Two examples on the protocol issues are briefly described below.

5.A. MPCP Extension and WDM IPACT

The multipoint control protocol (MPCP) is the basic MAC protocol adopted in EPON, which assigns time slots for each ONU's upstream transmission. The MPCP extension, proposed for EPON upgrade to WDM-PON, assigns not only time slots but also wavelengths in a WDM-PON system [44]. It assumes an array of fixed lasers or receivers at the OLT and either an array of fixed lasers or receivers or one or more tunable lasers or receivers at the ONU. During the discovery and registration process, the OLT receives information on each ONU's transmitter or receiver type (tunable or fixed), tuning time, and supported wavelengths using a 'REGISTER_REQUEST' message [44]. Upon receiving the upstream message, the OLT could keep track of the utilization of each wavelength and use this information for deciding on any wavelength-assignment changes. The wavelength-assignment information is carried in the "GATE" message. The "receiver-configuration" message is sent from the OLT to each ONU to reconfigure the ONU's filter. The "receiver-configuration acknowledge" message is sent from each ONU to the OLT. The special algorithm to utilize wavelengths efficiently in this process is called WDM-IPACT, which is the WDM upgrade of IPACT, one of the early proposals for a DBA protocol in EPONs [45].

5.B. WDM-PON DBA Protocol for SUCCESS Architecture

The SUCCESS-DWA PON architecture uses tunable lasers at the OLT and a filter at each ONU, so that any OLT can reach any ONU [43]. Each tunable laser is scheduled to communicate with several ONUs scattered over different ONU groups by hopping its wavelength. A WDM-PON DBA is suggested [46] for this purpose, which increases the throughput of the network by finding an appropriate wavelength for each traffic. Incoming signals from the backbone network are separated into high-priority (HP) and best-effort (BE) traffics and then provided to their own output queues, respectively, to be assigned to appropriate tunable lasers. A structure, where the HP traffic is directly provided to the wavelength scheduler while the BE traffic is temporally stored in the buffer for assignment, is suggested for better efficiency. The HP packet is given priority in finding a suitable tunable LD, and then the BE traffic is extracted from its queue when there is no incoming HP packet.

6. Services with WDM-PONS

The convergence of voice, data, and video on a single WDM-PON is expected to reduce the cost and also promote the creation of new services. Figure 14 shows a brief evolution (roadmap) of a broadband multiservice network. From the viewpoint of services, first there was a big wave of the Internet, followed by voice over IP (VoIP) and Virtual private network (VPN). These services required rapid increase of bandwidth, QoS for multimedia, and high availability of network resources. Networking technologies such as traffic engineering, highly available path protection, DiffServ, and multiservice were developed.

The next generation of services is expected to be the convergence of web and television. There will be integration of communication and broadcasting in the network and also integration of the personal computer and television in the user equipment. A broadcasting service such as CATV may be integrated with Internet-based services. Demand for multicasting services with high quality and specialized contents is also expected to increase. Many value-added applications such as high-quality on-demand video services, time-shifted television services, and television web portal (Walled Garden) can be created through this integration. This will promote and be in harmony with the concept of Digital Home.

These new services will require reliable, secure, economic, and abundant (possibly symmetric) bandwidth. Hence, in the backbone, scalable multicasting, advanced traffic engineering, video networking middleware, and storage networking technologies are required. Similarly, future access networks should be equipped with the capability of flexible bandwidth provisioning and multimedia multicast, bidirectional symmetry, fast response time, reliability and security, and QoS. SLA for customized QoS and security is another important requirement. Until recently, these issues were treated mainly in backbone networks. However, the arrival of true convergence gives the ability to access these services, and WDM-PON can be most competitive access technology.

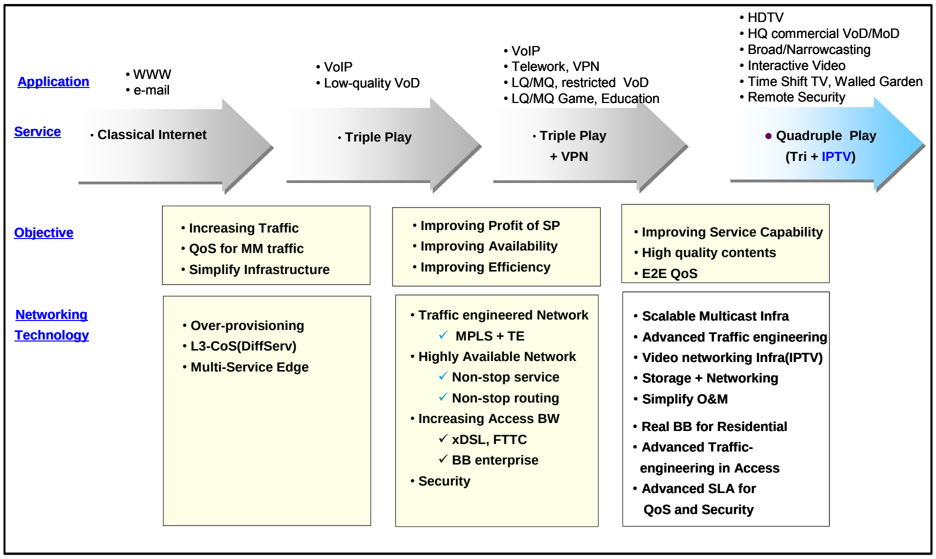

Fig. 14. Evolution (roadmap) of a broadband multiservice network.

Table 2 shows an example of broadband access requirements for an ordinary WDM-PON customer. Such a customer may have three video terminals at home and four family members, on average. The network might be heavily loaded at certain times, e.g., between 8 p.m. and 10 p.m. In a typical scenario, the father is watching a HDTV sports channel such as football, the mother is talking over the video phone, the daughter is attending an interactive education class, and the son is playing an on-line multiplayer game. The minimum downstream bandwidth required in the access network for such a family would be 70 Mbits/s. Additionally, the minimum upstream bandwidth should be approximately 30% of the downstream bandwidth. Also, QoS features for multimedia services, such as delay, jitter, and loss should be guaranteed and the availability of 99.95 to 99.999% should be assured. Additionally, fast response time is required; e.g., channel-zapping time must be similar to CATV during busy hours. From the service provider's viewpoint, efficient multicast and bandwidth utilization should be possible. The available bandwidth should be fairly shared among all customers while guaranteeing the SLA contract.

7. Summary

In this paper, we presented a comprehensive review on technologies for the WDM-PON. We focused on various aspects of device technologies, network architectures, and protocols and services for the WDM-PON. While traditionally, research in each of these areas has been independent without addressing the dependencies between the above aspects, we believe that our work illustrates the need for a tighter coupling between these topics.

Interestingly, it should be noted that all competing TDM PON architectures (namely, EPON, BPON, and GFP-PON) may be combined using CWDM on the same PON. Another good perspective on WDM-PON issues may be found in [47].

Table 2. Access-Network Requirements for an Ordinary WDM-PON Residential Customer

Features	Requirements
Bandwidth (bps)	• BW / Subscriber - Down: 3 x 20M(HDTV, MPEG-2) + α = **70M~80M** - Up: 30% of Down = 20M
QoS guarantee for Multimedia traffic	• Real-time Voice/Video - Latency, Jitter, Loss - Converged user equipment
Security	• Authorization, authentication • data confidentiality
Efficient Multicast	• Internet Group Management Protocol v3 • Efficient multicasting channel
Availability	• 99.95 ~ 99.999%
Response time	• Ex: Zapping time similar to CATV in busy hour • Less than ~ms for remote security
Efficient BW utilization	• Available bandwidth should be fairly shared between customers

We believe that, with increasing maturity of various technologies, the WDM-PON shall soon be at a point of consideration for commercial deployment to meet the high-bandwidth requirements in the broadband access network. As can be seen in our review, the research on device technologies for WDM-PON has received the most attention in the literature, while WDM-PON architectures have received moderate attention, with no clear winner emerging yet. To make an architecture useful, a suitable protocol is needed, and this is an area of research that is in its infancy for WDM-PONs. Significant attention ought to be provided to protocol aspects in order to make WDM-PONs viable.

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