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Optical Access Architecture Designs Based on WDM-Direct toward New Generation Networks

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SUMMARY   We present our proposed designs of optical access architecture based on WDM technology toward *new*-generation networks for two types of topologies: Single-star (SS) and passive-double-star (PDS). We adopt the concept of *WDM-direct* which links multiple wavelengths to each optical network unit (ONU). Our proposed architecture based on WDM-direct can achieve more than 10 Gbps access per ONU. Moreover, our architecture can provide not only conventional bandwidth-shared services but also bandwidth-guaranteed services requiring more than 10 Gbps bandwidth by establishing end-to-end lightpaths directly to each ONU, and thus meet high requirements of QoS in new-generation networks. Firstly, we show our proposed designs of *SS-type* architecture, and experimentally demonstrate the system. We confirm that the optical line terminal (OLT) successfully switches between packet/lightpath data transmissions for each ONU. In addition, we measure and evaluate optical power loss in upstream/downstream transmissions between the OLT and ONUs. Secondly, we show our proposed designs of *PDS-type* architecture, and theoretically analyze and evaluate the bit-rate capacity of the system.
key words: *optical access architecture, new generation networks, WDM, lightpath, single star, passive double star*

1. Introduction

In recent years, the number of subscribers to the Fiber-To-The-Home (FTTH) has been rapidly increasing due to the advantage of high-speed Internet access. The number of subscribers to the FTTH exceeded 14 millions in Japan at the end of 2008. In addition, infrastructure is in place that will potentially enable more than 40 millions users to subscribe [1], and we expect that the number of subscribers will continue to increase in the future.

As for optical access networks, Gigabit Ethernet-Passive Optical Network (GE-PON) [2], [3] and Gigabit-PON (G-PON) [4], [5] have been already commercialized owing to the benefits of low-cost and high-speed (10–100 Mbps) Internet access. For *next*-generation networks of which building will be completed by the year 2010, 10G-EPON and XG-PON will be developed, and would be commercially available in 2011–2012 [6]–[9].

As another type of PON, wavelength-division-multiplexing (WDM)-PON has gained increasing attention [10]–[12]. WDM-PON assigns a dedicated wavelength to each optical network unit (ONU) through an arrayed waveguide grating (AWG), and has a potential for providing Gbps-class network access to each ONU.

On the other hand, traffic continues to increase currently, and if we estimate a 1000-fold increase in 13 years (1.7 times per year), high-speed access exceeding 10 Gbps will be required for each user to realize the information network of 2020 and beyond (that is, the *new*-generation network). The current or even next-generation time-division-multiplexing (TDM)-based PONs such as GE-PON/G-PON have difficulty of guaranteeing QoS for applications which require wide bandwidth (e.g. from a few Gbps to Tbps) and real-time properties because all users share the bandwidth through a coupler. The current WDM-PON assigns only one dedicated wavelength to each ONU because of lacking in demands for wide bandwidth. Furthermore, the WDM-PON has difficulty in providing multicast/broadcast communications in comparison to the GE-PON/G-PON.

For all of these reasons, the next-generation 10G-EPON, XG-PON and WDM-PON are not suitable for new-generation networks that we aim to commercialize by the year 2020. Therefore, before the current or next-generation optical access systems reach their limits, we must create an architecture, planning and design of optical access suited for new-generation networks without being impeded by any constraints on existing techniques/demands.

Recently, we have worked on new-generation optical access architecture based on WDM technology for each of two types of topologies: single-star (SS) and passive-double-star (PDS) as a part of the AKARI Architecture Design Project launched in April 2006 [13], [14]. In this paper, we present our proposed designs of optical access architecture toward new-generation networks for both SS and PDS. Our proposed architecture adopts the concept of *WDM-direct* that links WDM directly to each ONU, which can achieve more than 10 Gbps access per ONU. Moreover, our architecture can provide not only conventional bandwidth-shared services (e.g. current Internet services) but also bandwidth-guaranteed services requiring more than 10 Gbps bandwidth by setting up end-to-end lightpaths directly to each ONU in new-generation networks. Firstly, we show our proposed designs of *SS-type* architecture, and establish and demonstrate an experimental setup of 25 km-long, WDM-based, SS-type new-generation optical access providing both bandwidth-guaranteed and bandwidth-shared services [15]. We confirm that the optical line terminal (OLT) successfully switches between packet/lightpath data transmissions for each ONU. In addition, we measure and evaluate optical power loss in upstream/downstream trans-

missions between the OLT and ONUs. Secondly, we show our proposed designs of *PDS-type* architecture, and theoretically analyze and evaluate the bit-rate capacity of the system.

2. Current FTTH

In Japan, FTTH services are provided by using SS and PDS. PDS is a term that expresses the form of network, and is often referred as passive optical network, PON. Currently, SS-topology is introduced mainly for condominium/office buildings whereas PON-topology is introduced mainly for isolated house. They both have antithetical advantages and disadvantages based on their respective topologies. For example, SS-type systems have the advantages that they can provide dedicated access lines to subscribers, they are transparent between the OLT and ONUs, and they can reliably and safely provide or upgrade different services separately (they have excellent expandability) [16], [17]. Although the high cost of providing the current 100 Mbps-grade services has been pointed out, once the fiber infrastructure is installed, upgrade costs are limited to only costs for individual ONUs and associated OLTs, and migration is easy. In addition, since there is little signal loss compared with a PON, it is also suited for long-distance users. Therefore, when looking towards the future, there are sufficient advantages in using SS topology for access infrastructure. On the other hand, the advantages of PON topology, which are the current mainstream optical access networks, are that they can conserve the number of fibers that are laid from the OLT, reduce OLT installation costs more than SS, and enable downstream broadcast communications (from the OLT towards the ONUs) to be easily performed. FTTH service-oriented standardization has been performed for PON. For example, the ITU-T has standardized G-PON (ITU-T G.984, 1.25 Gbps or 2.4 Gbps, accommodates up to 64 ONUs, supports distances up to 20 km). The IEEE has standardized GE-PON (IEEE 802.3ah Ethernet PON, 1.25 Gbps, accommodates at least 16 ONUs, supports distances up to 10 km or 20 km). Currently, in Japan, many services providing up to 100 Mbps to each home have been introduced on both SS and PON.

3. Next-Generation PON

3.1 10G-EPON, XG-PON and WDM-PON

Optical access methods using TDM-based protocols such as GE-PON or G-PON will become the mainstream access methods of optical access networks even in next-generation networks expected to be completed by 2010. 10G-EPON [6], [7] and XG-PON [8], [9], in which the bandwidth of entire existing GE-PON and G-PON networks is upgraded from 1 Gbps to 10 Gbps, are expected to be introduced, and the standardization of 10G-EPON technology by IEEE802.3av is progressing and is expected to be completed by 2009 [18], [19]. On the other hand, as another
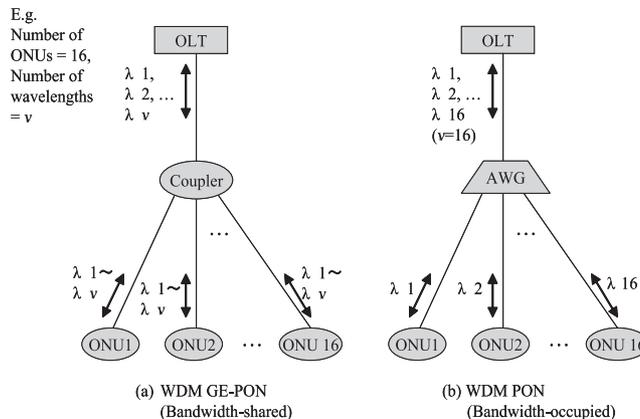
Fig. 1   (a) WDM GE-PON and (b) WDM-PON.

next-generation PON, WDM GE-PON [22], in which WDM functions have been added to transmitters/receivers in conventional GE-PON using couplers, has been attracting attention and discussed in ITU-T as a next-generation access (NGA) [18], [19]. WDM GE-PON can increase the number of wavelengths or capacity by using WDM with practically no changes to the existing optical infrastructure or protocols. Dual-rate PON, in which 1 Gbps users' signals and 10 Gbps users' signals are mixed within the same network [6], [20], [21], is expected to be implemented by first upgrading only ONUs requesting 10 Gbps data transfers to 10 Gbps. Dual-rate PON has a merit that each ONU can reduce power consumption by decreasing the bit-rate from 10 Gbps to 1 Gbps when the amount of data traffic is small.

However, since these kinds of PON methods provide services by sharing bandwidth among multiple ONUs, they have a problem in that the bandwidth that can be sent or received by one ONU gets narrower as the number of branches or the distance increases. For example, if 10G-EPON splits the 10 Gbps bandwidth in 32, it only achieves 300 Mbps per ONU in average. However, a costly (although not as expensive as the current one) 10 Gbps interface must be introduced. In the existing access infrastructure using couplers, communication capacity is limited due to aerial overhead wiring or splitting loss, and it may be difficult to guarantee quality of service (QoS) for bandwidth exceeding the capacity when traffic rapidly increases. In addition, the system has to equip new optical amplifiers to compensate for splitting loss, depending on the degree of multiplexing or communication speed.

In addition, WDM-PON [10]–[12] has been attracting attention as another next-generation PON. As we illustrate in Fig. 1, WDM-PON differs from a method using couplers such as WDM GE-PON, which we described earlier, in that it has an AWG instead of a star coupler at the intermediate node and a single wavelength is uniquely assigned to each ONU. WDM-PON, which is still at the scientific research and experiment stage, has not yet been standardized. Generally, an AWG has much lower insertion loss than an optical coupler. Besides, by using the AWG to assign one wave-

length to each user, WDM-PON enables users to occupy and use separate bandwidths like in SS. Thus, it enables faster access than with GE-PON and G-PON, which provide services according to bandwidth-shared protocols using a coupler, and can guarantee QoS relatively easily. However, in addition to there being no current demand for wide bandwidth exceeding 10 Gbps per ONU, the performance of existing optical devices is limited, and most research and development focuses on WDM-PON that assumes one wavelength (155 Mbps to 10 Gbps) per ONU. In addition, since WDM-PON differs from GE-PON and G-PON in that an AWG is installed at the intermediate node instead of a coupler, it also has the disadvantages that it cannot provide Internet services according to bandwidth-shared protocols as are done conventionally and it makes it more difficult to perform multicast/broadcast communications than GE-PON and G-PON.

4. Proposed Optical Access Architecture toward New Generation Networks

From an application viewpoint, bandwidth-guaranteed services that can guarantee QoS for applications that require real-time capabilities and several Gbps to Tbps class speeds (e.g. digital cinema, 3D video, online game, eHealth etc), which will appear in the future, will be required in addition to conventional Internet (bandwidth-shared) services. However, we expect that guaranteeing QoS for applications that require more than 10 Gbps speeds is difficult in current and next-generation PONs. On the other hand, from an optical device viewpoint, we expect that advanced WDM optical devices capable of sending/receiving 10 Gbps per wavelength in addition to multiple wavelengths simultaneously will be commercialized in the future. Under the assumption that the application requirements and device commercialization described above will become more likely, we are investigating a new-generation optical access architecture using a basic concept that is called *WDM-direct*.

4.1 WDM-Direct

WDM-direct is a concept in which multiple wavelengths are directly connected to each ONU. For new-generation optical access, we assume there will be multiple wavelength assignment requests for each ONU rather than just one wavelength as in next-generation WDM-PON. With this method, data can be transmitted/received using multiple wavelengths simultaneously to perform, for example, Internet (bandwidth-shared) services with a certain group of wavelengths and bandwidth-guaranteed services with a separate group of wavelengths. The system can also use one wavelength or group of wavelengths for broadcasting/multicasting. WDM-direct can be introduced to any types of network topologies (i.e. both PON and SS). In new-generation networks, not only large-scale optical backbone network but also optical access will be required to guarantee QoS by means of data transmissions on lightpaths. Here, we define *light-*
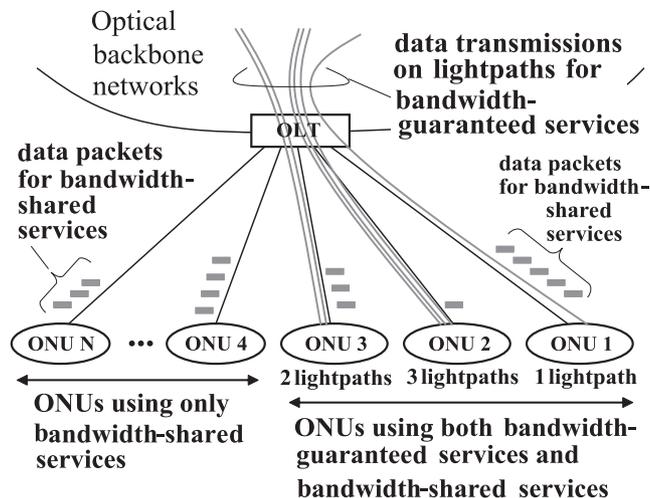

Fig. 2 Our proposed basic design of new-generation SS architecture.

path as optical logical circuit of which the bandwidth is occupied and guaranteed from source to destination. In this work, each link occupies one or more wavelengths as optical logical circuits. We assume that all intermediate nodes avoid optical-electrical-optical (O/E/O) conversions for data transmissions on lightpaths, but can perform wavelength conversions. To provide end-to-end transparent bandwidth-guaranteed services, one or more lightpaths must be set up from the source ONU via the optical backbone network to the destination ONU without O/E/O conversions.

Here, we explain why we propose two types of optical access architectures toward new-generation networks: SS-type and PDS-type. In current optical access system, these two topologies are major and introduced in different types of buildings each other as we described in the Chapter 2. Owing to their simple structures, we strongly believe that the two topologies will continue to be mainstream also in future networks. Note that, if cost of optical equipments and their management will become sufficiently low, the ultimate topology for optical access system is SS. Thus, we propose a SS-type new-generation optical access architecture. Meanwhile, current optical access networks for house mainly adopt PDS topology, due to its advantage that can save in the number of fibers connected to an OLT. Therefore, in this paper, we also propose a PDS-type new-generation optical access architecture as a scenario for migration to the SS-type architecture.

### 4.2 Proposed SS-type Optical Access Architecture

4.2.1 Basic Design

Figure 2 illustrates our proposed basic design of SS-type new-generation optical access architecture using WDM-direct. This is the example in which ONU1, ONU2 and ONU3 use bandwidth-guaranteed services by establishing 1, 3 and 2 lightpaths, respectively. In SS, each ONU is directly connected to the OLT by a dedicated optical fiber. There-

fore, each ONU can receive both bandwidth-shared services and bandwidth-guaranteed services by using only one optical fiber. Optical packets of bandwidth-shared services are terminated at the OLT by use of an optical-electrical conversion in the conventional manner, and are transferred in optical backbone networks by means of bandwidth-shared protocols. In other words, as in the conventional Internet services, the system does not always guarantee bandwidths of data prepared for bandwidth-shared services between source and destination. To provide end-to-end transparent bandwidth-guaranteed services, our SS architecture guarantees QoS by setting up end-to-end lightpaths from each source ONU via optical backbone networks to the destination without any O/E/O conversions. Note that the number of established lightpaths depends on the bandwidth required for the bandwidth-guaranteed services. Signaling information to establish lightpaths can be sent by taking advantage of data prepared for bandwidth-shared services. In this way, our proposed architecture guarantees QoS by setting up multiple end-to-end lightpaths, depending on the required bandwidth, for an ONU that requires guaranteed bandwidth, while providing conventional bandwidth-shared services using conventional packet transfers.

4.2.2 Detailed Design

Figure 3 illustrates (a) the OLT structure and (b) the ONU structure of our proposed SS-type new-generation optical access architecture. At the OLT, an AWG demultiplexes WDM signals received from each ONU, and the optical cross-connect (OXC) transfers each wavelength signal to the packet section or lightpath section depending on the service. The packet section begins by converting received optical signals to electrical ones, and processes data packets transferred for bandwidth-shared services. When an ONU requests the OLT to change the OXC configuration, the ONU sends signaling information to the packet section. If the OLT receives the signaling information, the controller switches the corresponding connections between the packet section and lightpath section. The lightpath section transfers data of bandwidth-guaranteed services to optical backbone networks in upstream transmissions or to each ONU in downstream transmissions without any O/E/O conversions. At an ONU, a colorless AWG demultiplexes the WDM signals received from the OLT. We define "*colorless AWG*" as an AWG device that is capable of using a cyclic characteristic [23]. According to the cyclic characteristic, group of wavelengths having the frequency spacing that matches the FSR (Free Spectral Range) of AWG are output from the same port. In this way, a colorless AWG can transfer multiple wavelengths per output port. The colorless AWG ports transferring "$\lambda_{x1}, \lambda_{x3}, \cdots \lambda_{x(m-1)}$" (m: positive even integer) handle downstream transmissions, and the other ports transferring "$\lambda_{x2}, \lambda_{x4}, \cdots \lambda_{xm}$" handle upstream transmissions. Transmitted and received signals are modulated and demodulated, respectively, by the transceiver. If a port inputs or outputs multiple wavelengths, an additional AWG

(a) The OLT structure

(b) The ONU structure
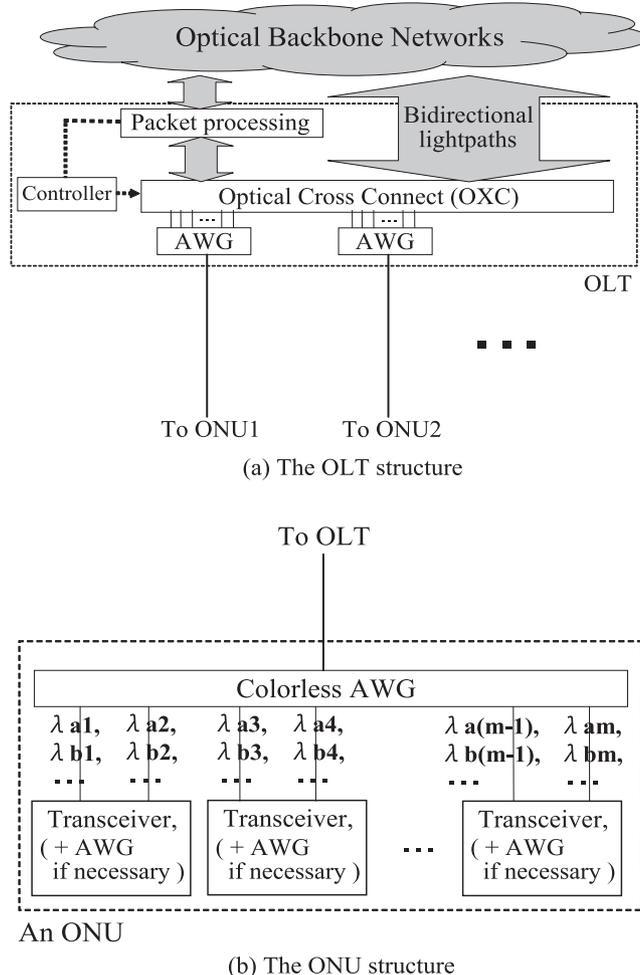
Fig. 3 Our proposed detailed design of new-generation SS architecture.

is equipped behind the colorless AWG port. Otherwise, no additional AWG is equipped.

4.2.3 Experimental Setup

Figure 4 illustrates our experimental setup of the proposed SS-type new-generation optical access using three wavelengths. We predict that each wavelength will have 10 Gbps bandwidth in new-generation optical access. However, in this experiment, we employ small form-factor pluggable (SFP) transceivers with 1.25 Gbps per wavelength because the SFP is enough to show our basic concept of WDM-direct. The link layer is Gigabit Ethernet (GbE). In future works, we will use 10 Gbps transceivers such as 10-Gigabit small form-factor pluggable (XFP). We define upstream transmission as data communication from SFPs in each ONU to SFPs in the OLT. We also define downstream transmission as data communication from SFPs in the OLT to SFPs in each ONU. In upstream transmissions, 193.3 THz-SFPs, 193.5 THz-SFPs and 193.8 THz-SFPs receive 193.2 THz signals, 193.4 THz signals and 193.7 THz signals, respectively. Likewise, in downstream transmissions, 193.2 THz-SFPs, 193.4 THz-SFPs and 193.7 THz-
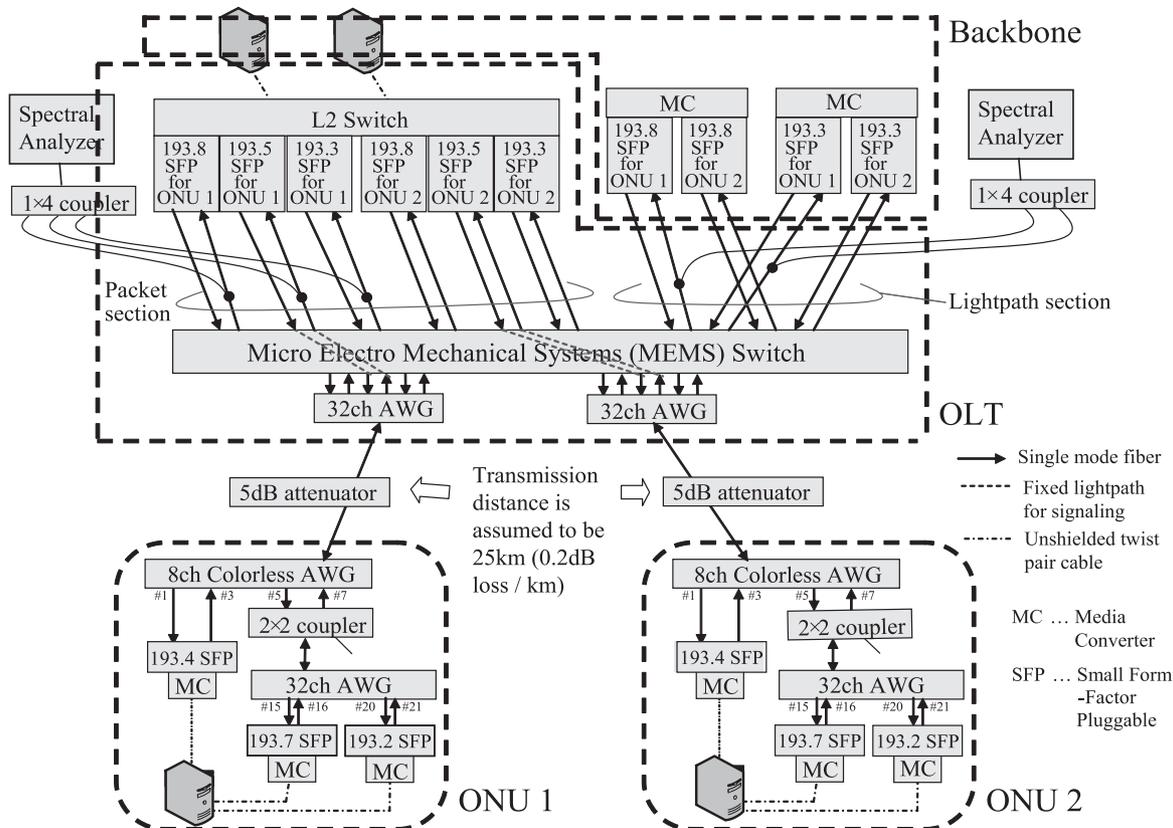
Fig. 4 Experimental setup of the new-generation SS architecture using 3 wavelengths.

SFPs receive 193.3 THz signals, 193.5 THz signals and 193.8 THz signals, respectively. The optical Micro-Electro-Mechanical Systems (MEMS) switch corresponds to the OXC illustrated in the Fig. 3(a). Each port of MEMS handles one wavelength to transfer data. This experimental setup employs 193.4 THz and 193.5 THz signals for the control plane on which the system automatically establishes lightpaths by means of signaling information originating from each ONU. These two kinds of signals are always transferred to the packet section via the OXC. Note that, in actuality, the system can use the two wavelengths also for data transmissions. We equip a 5 dB attenuator between the OLT and each ONU because we assume the transmission distance between them is 25 km. In this experimental setup, we assume that each set of media converter (MC)+SFPs for the lightpath section is a core node placed within optical backbone networks. Since our proposed architecture is supposed to transfer data on lightpaths without any O/E/O conversions, we would be obligated to equip an optical circuit switch or all-optical wavelength converter rather than the MC for the lightpath section. However, we substitute the MC because, in this work, we only evaluate the optical power loss in each of upstream/downstream transmissions between the OLT and ONU. We confirmed that the system successfully demonstrates upstream/downstream transmissions by *ping* (i.e. ICMP sending/receiving).

Figure 5 shows the spectral lines of upstream optical signals at the OLT received from ONU1. We observed the spectral lines by using the spectral analyzer equipped at the OLT side as shown in Fig. 4. In case (a), ONU1 receives only bandwidth-shared services. Figure 5(a) shows that the peaks are launched at all wavelengths in the packet section, and the lightpath section has no peak values. We can see that the peak value of 193.4 THz is higher than those of 193.7 THz/193.2 THz. This is because 193.4 THz signals get through less number of optical devices in data transmissions between the OLT/ONU as we can see in Fig. 4, and thus experiences less value of loss in comparison to 193.7 THz/193.2 THz signals. In case (b), ONU1 uses bandwidth-guaranteed services by employing the 193.7 THz signal. We can see only the peak of 193.7 THz is switched from the packet section to the lightpath section. (Just for the record, we also confirmed the peak of 193.2 THz can be switched between the packet/lightpath sections.) We can say that the OLT successfully switches the connection between packet/lightpath data transmissions for the ONU.

4.2.4 Measurement of Optical Power Loss

Table 1 shows the measured power loss in upstream/downstream transmissions between the OLT and ONUs. Here, according to the specifications of optical devices, we estimate that the optical power loss is −27.5 dB and its fluctuations are −5.5 to +7.5 dB. The power loss is the gap between the two power levels: the transmitted power at the SFP in the transmitter side and the received power at the SFP
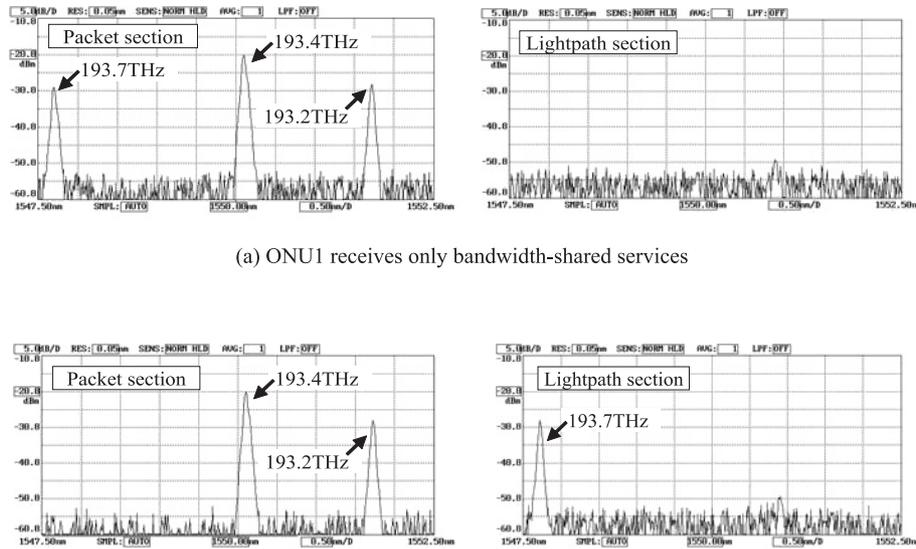
(a) ONU1 receives only bandwidth-shared services

(b) ONU1 receives bandwidth-guaranteed services by employing the 193.7THz signal

Fig. 5 Spectral lines of optical signals at the OLT received from ONU1 (Upstream transmissions).

Table 1 Measured values of optical power loss.

	ONU1 (dB)	ONU2 (dB)
Upstream	−27.5 to −27.3	−25.1 to −24.5
Downstream	−28.0 to −27.5	−25.1 to −23.9

in the receiver side. We obtained the experimental results of power loss values that are fairly close to the value estimated by the specifications. The slight gap would be caused by the degrees of precision of optical devices.

4.3 Proposed PDS-Type Optical Access Architecture

4.3.1 Basic Design

Figure 6 illustrates our proposed basic design of PDS-type new-generation optical access architecture based on WDM-direct. Generally, a double star configuration uses a topology that installs an intermediate node between the OLT and ONUs, and optical fibers are wired in a star configuration centered on that intermediate node. We often call the intermediate node *remote node* (RN). In Fig. 6, we define downstream transmission as the signal flow from the OLT to ONUs, and upstream transmission as the one from ONUs to the OLT.

In our proposed optical access architecture, the RN equips a coupler and a colorless AWG in parallel in the configurations for providing both bandwidth-shared services and bandwidth-guaranteed services. The OLT and RN are connected by two fibers that are respectively linked to the coupler and the colorless AWG. The fiber connected to the coupler is used for bandwidth-shared services whereas the other one connected to the colorless AWG is used for bandwidth-guaranteed services. The OLT equips an optical switch (e.g. MEMS) in order to transfer each wave-
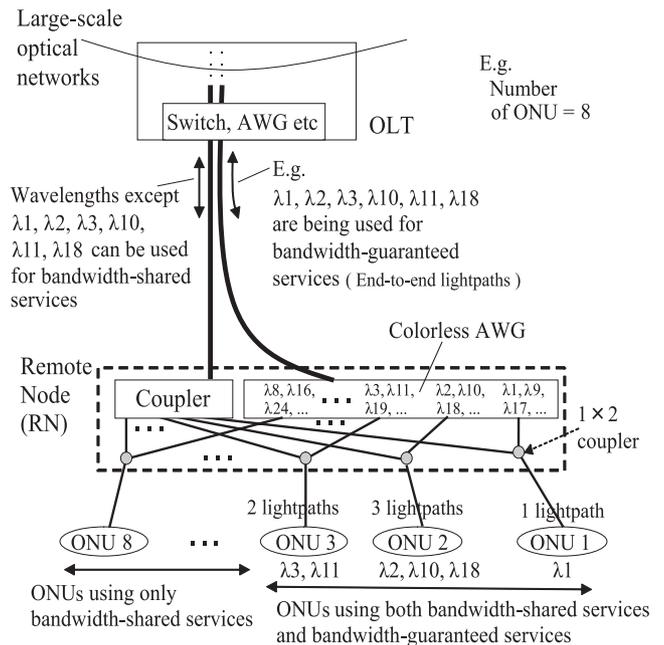
Fig. 6 Our proposed basic design of new-generation PDS architecture. (E.g. The number of ONUs is 8. λ_1, λ_2, λ_3, λ_{10}, λ_{11} and λ_{18} are being used for bandwidth-guaranteed services (i.e. lightpaths).)

length signal to either one of two fibers connected to the coupler/colorless AWG in the RN in downstream transmissions and to backbone networks in upstream transmissions. In the RN, a 1×2 coupler aggregates the two fibers. Each of the fibers is connected to the coupler output-port and colorless AWG output-port respectively. Each 1×2 coupler in the RN is connected to the corresponding ONU by a dedicated fiber. In the example of Fig. 6, we assume that the number of ONUs $N=8$ and the colorless AWG in the RN can transfer

multiple wavelengths at one output-port in both upstream and downstream transmissions. A number of wavelengths corresponding to the bandwidth request are dedicated to each ONU using bandwidth-guarantee services. In other words, our proposed architecture guarantees the requested bandwidth by directly setting up lightpaths of one or more wavelengths directly to the ONU. Bandwidth-shared services are provided by sharing the group of wavelengths that are not being used by bandwidth-guaranteed services among all ONUs via the coupler. In the example of Fig. 6, ONU 1, ONU 2 and ONU 3 use one wavelength (λ_1), three wavelengths (λ_2, λ_{10}, λ_{18}), and two wavelengths (λ_3, λ_{11}), respectively, to send data traffic on lightpaths through the colorless AWG in unidirectional transmissions. Note that we assume that upstream and downstream lightpaths are assigned separate wavelengths each other. All other wavelengths can be shared by all ONUs in order for providing bandwidth-shared services. As in our proposed SS-type architecture, the OLT performs the O/E/O conversion for data signals transferred via the coupler in both upstream and downstream transmissions. When an ONU using only bandwidth-shared services desires to receive bandwidth-guaranteed services newly, the system guarantee QoS by controlling the optical switch in the OLT to set up end-to-end lightpaths with a number of wavelengths according to the bandwidth request through the colorless AWG.

The proposed PDS-type optical access architecture has the following advantages:

- Conventional Internet users can receive bandwidth-shared services according to a conventional method such as GE-PON and G-PON. Moreover, vast amount of bandwidth that exceeds 10 Gbps per ONU and QoS guaranteed functions can be provided to ONUs which desire to use bandwidth-guaranteed services by establishing multiple end-to-end lightpaths.
- Even when an ONU has used all wavelengths of the dedicated AWG output port for bandwidth-guaranteed services, it enables the ONU to receive bandwidth-shared services by using separate wavelengths that are not being used by other ONUs through the coupler.
- It enables broadcasting/multicasting in the downstream direction to easily be performed via the coupler.

4.3.2 Detailed Design

Figure 7 illustrates (a) the OLT structure and (b) the ONU structure of our proposed PDS-type new-generation optical access architecture. The OLT structure is similar to that of our proposed SS-type architecture, but has slightly different structure in which only two fibers are installed between the OLT and RN: one is for the coupler (i.e. bandwidth-shared services) and another is for the colorless AWG (i.e. bandwidth-guaranteed services). In this example, we assume the number of ONUs is 8. Each 1×2 coupler aggregates the two output fibers connected to the coupler/colorless AWG, and a dedicated fiber is installed to each

(a) OLT structure

(b) ONU structure
(Example of ONU1)
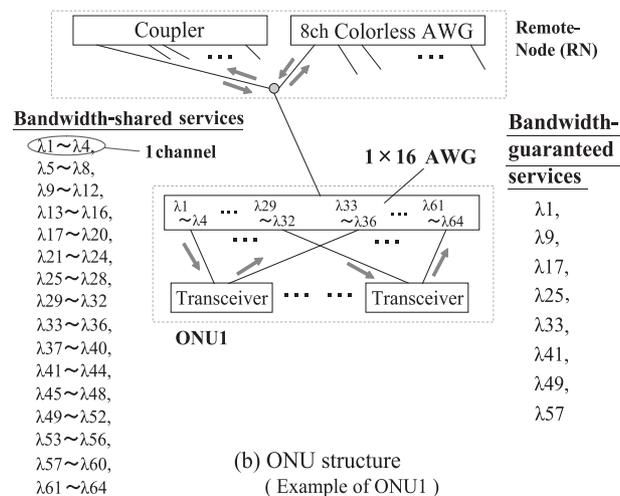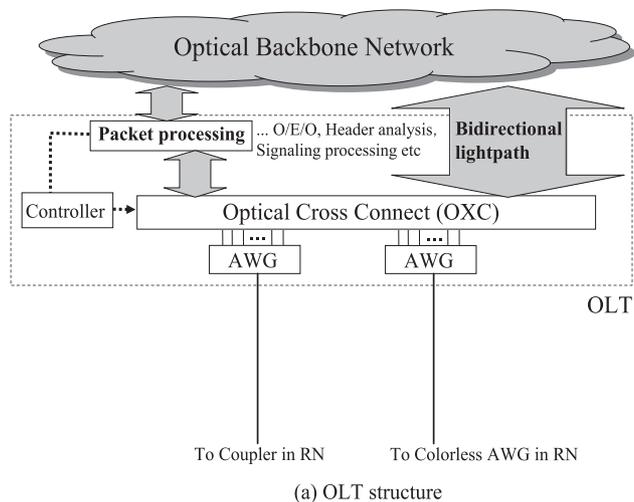
Fig. 7 Our proposed detailed design of new-generation PDS architecture. (E.g. Number of ONUs is 8. Total number of wavelengths are 64 and each ONU can employ up to 8 wavelengths (lightpaths) for bandwidth-guaranteed services (The sum of upstream and downstream). Optical packets of bandwidth-shared services are transferred by regarding 4-wavelengths as 1-channel.)

ONU. In an ONU, the 1×16 AWG multiplexes or demultiplexes the WDM signals from the transceivers or the RN, respectively. The system assigns λ_w to ONUx ($w = x + 8y$, $x \in (1, 2, \cdots, 8)$, $y = (0, 1, \cdots, 7)$) in order to provide bandwidth-guaranteed services. Figure 7(b) is the example of ONU1 (i.e. $x = 1$). As illustrated in Fig. 7(b), employing the 64 wavelengths for bidirectional transmissions, the system can assign half of the wavelengths to upstream data transmissions and the other half to downstream data transmissions. In this example, the system employs the wavelengths with "$w \leq 32$" and "$w > 32$" for downstream and upstream data transmissions, respectively.

Data transmissions transferred for bandwidth-shared services experience the coupler loss that is much larger than the loss of the colorless AWG. Hence, we need to increase the transmitted optical power per channel for bandwidth-

shared services so that the optical power of a signal received from the coupler can be kept the same level of that of a signal received from the colorless AWG. Here, we define *channel* as a band required for sending a bit information. For bandwidth-guaranteed services, one channel includes only one wavelength. However, for bandwidth-shared services, the ONU is obliged to send or receive the same bit information over multiple wavelengths in order to increase the received optical power. In other words, to keep the same received optical power per bit regardless of the services, one channel in data packets of bandwidth-shared services must include multiple wavelengths. For example, if the gap between the coupler loss and the AWG loss is 6 dB, the system needs to increase the transmitted optical power per channel by a factor of 4 for bandwidth-shared services in order to keep the received optical power constant. Thus, the system needs to transfer optical packets of bandwidth-shared services by regarding 4-wavelengths as 1-channel. In Fig. 7(b), "$\lambda_{4z+1} \sim \lambda_{4z+4}$" ($z \in 0, 1, \cdots, 15$) is regarded as 1 channel.

4.3.3 Theoretical Analysis and Evaluations of Bit-Rate Capacity

We analyze and evaluate the bit-rate capacity of our proposed PDS-type optical access architecture by use of the following parameters;

- P_t: Transmitted optical power of all wavelengths at the OLT (dBm)
- α: Maximum loss at the OXC in the OLT (dB)
- β: Maximum loss at the AWG in the OLT or ONU (dB)
- γ: Insertion loss at the coupler in the RN (dB)
- δ: Total loss at the coupler in the RN (dB)
- ϵ: Maximum loss at the Colorless AWG (dB)
- ζ: 1×2 splitter loss (dB)
- η: Transmission loss (dB/km)
- L: Transmission distance (km)
- P_r: Received optical power per wavelength at an ONU (dBm)

In this study, we assume that $P_t = +27$, $\alpha = 3$, $\beta = 4.5$, $\gamma = 4.5$, $\epsilon = 7.5$, $\zeta = 3$, $\eta = 0.2$, $L = 25$, $P_r = -24$. Here, δ is the sum of the insertion loss and the splitting loss at the coupler, which is expressed as $\delta = \gamma + \lfloor 10\log_{10}N \rfloor$ where N is the number of ONUs. $\lfloor t \rfloor$ means the maximum integer that is equal to or smaller than t. Note that we show the bit-rate capacity in one-way transmission in this analysis.

(1) Bit-rate capacity for bandwidth-guaranteed services
First, we analyze the bit-rate capacity for bandwidth-guaranteed services. The maximum number of wavelengths in the colorless AWG, W_{g-max}, can be obtained by calculating the maximum value of W_g that meets the following equation;

$$P_t - (\alpha + \beta + \epsilon + \zeta + \beta + \eta \times L)$$
$$\geq 10\log_{10}(W_g) + P_r. \tag{1}$$

Using the above parameter values, we can obtain $W_{g-max} =$

Table 2 Maximum guaranteed bit-rate per ONU for bandwidth-guaranteed services.

N	R_{b-g}
8	270 Gbps (27-lightpaths $\times$ 10 Gbps)
16	130 Gbps (13-lightpaths $\times$ 10 Gbps)
32	60 Gbps (6-lightpaths $\times$ 10 Gbps)
64	30 Gbps (3-lightpaths $\times$ 10 Gbps)

223. Then, the upper bound of number of wavelengths per ONU, W_{g-ONU}, is given by

$$W_{g-ONU} = \lfloor W_{g-max}/N \rfloor. \tag{2}$$

The guaranteed bit-rate per ONU, R_{b-g}, is given by

$$R_{b-g} = 10 \times W_{g-ONU}, \tag{3}$$

where "10" means that one wavelength has 10 Gbps bandwidth.

Table 2 shows the upper bound of guaranteed bit-rate on end-to-end lightpaths per ONU for bandwidth-guaranteed services, R_{b-g}, in the case of $N = 8$, 16, 32 and 64. We can see that, as the value of N increases, the guaranteed bit-rate decreases. This is because the total number of wavelengths in the network, W_{g-max}, is a fixed value, and thus the increase of ONUs results in the decrease of bandwidth per ONU.

Note that the system will be able to increase the upper bound of bit-rate capacity if each optical device will be able to decrease the value of loss along with future growth of device technologies.

(2) Bit-rate capacity for bandwidth-shared services
Next, we analyze and evaluate the number of channels which all ONUs share for bandwidth-shared services, W_c. As we explained in Sect. 4.3.2, data transmissions transferred for bandwidth-shared services experience the coupler loss (δ) which is much larger than the loss of the colorless AWG (ϵ). Hence, in order to keep $P_r = -24$ also for bandwidth-shared services, we need to increase the transmitted optical power per channel by regarding multiple wavelengths as one channel. We denote the number of wavelengths in one channel by X, which is expressed as

$$X = Ic(10^{(\delta-\epsilon)/10}). \tag{4}$$

where $Ic(u)$ is the positive integer which is closest to the value of u. For example, when the number of ONUs $N = 8$, the gap between the coupler loss and the AWG loss is 6 dB, and we obtain $X = 4$. As a result, we need to increase the transmitted optical power per channel by a factor of 4 in order to keep $P_r = -24$, and therefore our proposed PDS-type optical access transfers optical packets of bandwidth-shared services by regarding 4-wavelengths as 1-channel. When $N = 16$, 32 and 64, we obtain $X = 8$, 16 and 32, respectively.

The bit-rate capacity for bandwidth-shared services depends on the number of lightpaths utilized in the colorless AWG because, to provide bandwidth-shared services, our PDS-type architecture uses the wavelengths that are not being used by bandwidth-guaranteed services. Be-

sides, note that the capacity also depends on which wavelengths the ONUs are using for bandwidth-guaranteed services. In the example of Fig. 7(b) (N = 8), we assume that the total number of wavelengths is 64 and 1-channel includes 4-wavelengths for bandwidth-shared services. This means that the system can use at most 16-channels for bandwidth-shared services when no ONUs receive bandwidth-guaranteed services. If ONU1 and ONU2 are using λ_1 and λ_2, the system can use at most 15-channels for bandwidth-shared services because λ_1 and λ_2 are included in the same channel. If ONU1 and ONU2 are using λ_1 and λ_{10}, the system can use at most 14-channels for bandwidth-shared services because λ_1 and λ_{10} are included in the separate channels. Therefore, in this analysis, we clarify the "average" available number of channels shared by all ONUs for bandwidth-shared services.

We denote the total number of wavelengths being utilized in the colorless AWG (i.e. for bandwidth-guaranteed services) by W_{AWG}. We define W_{cm-N} as the maximum available number of channels for bandwidth-shared services in the case that the number of ONUs is N and $W_{AWG} = 0$, which can be expressed as $\lfloor N \cdot W_{g-ONU}/X \rfloor$. When N = 8, 16, 32 and 64, we obtain W_{cm-N} = 54, 26, 12 and 6, respectively. We also define J as the number of channels being utilized in the W_{cm-N} channels. Then, we can obtain the average available number of channels for bandwidth-shared services, W_{c-av}, by

$$W_{c-av} = W_1/W_2,$$

$$W_1 = \sum_{J=k}^{min(W_{AWG}, W_{cm-N})} ({}_{W_{cm-N}}C_J) \cdot Pr(W_{AWG}, J) \cdot (W_{cm-N} - J),$$

$$W_2 = \sum_{J=k}^{min(W_{AWG}, W_{cm-N})} ({}_{W_{cm-N}}C_J) \cdot Pr(W_{AWG}, J). \qquad (5)$$

Note that the upper bound of W_{c-av} (i.e. when W_{AWG} = 0) is equal to W_{cm-N}. Here, $Pr(W_{AWG}, J)$ is all combinations of number of wavelengths in each of the J (i.e. utilized) channels under the given values of W_{AWG} and J. Also, we assign the value of k obtained by the following conditional equation;

$$k = z$$

$$\text{when } X \cdot (s - 1) < W_{AWG} \leq X \cdot s$$

$$(s \in (1, 2, \cdots)) \qquad (6)$$

Equation (6) means that the number of wavelengths in one channel is limited to X for bandwidth-shared services. For example, when N = 8 (i.e. X = 4) and W_{AWG} = 5, the value of J certainly exceeds 1 because one channel cannot include more than 4 wavelengths.

Figure 8 shows the total number of lightpaths being utilized via the colorless AWG (W_{AWG}) versus the average available number of channels shared by all ONUs for bandwidth-shared services (W_{c-av}). We can see that the increase of W_{AWG} results in the decrease of W_{c-av}. This means that the number of channels which can be used for
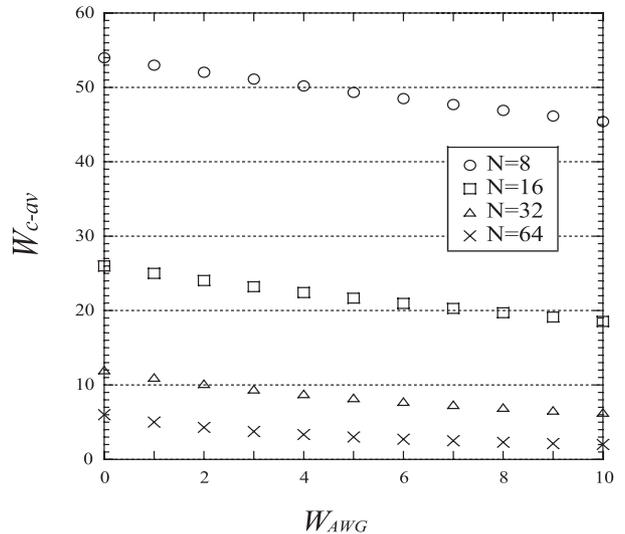
Fig. 8 Total number of lightpaths being utilized via the colorless AWG (W_{AWG}) versus the average available number of channels shared by all ONUs for bandwidth-shared services (W_{c-av}).

bandwidth-shared services is decreased by lightpaths established for bandwidth-guaranteed services. As we explained earlier, our architecture reliably guarantees the bit-rate per ONU described in Table 2 for bandwidth-guaranteed services. At the same time, any ONU can send data prepared for bandwidth-shared services by using the shared wavelengths of which the average available number can be seen in Fig. 8. For example, when N = 32 and W_{AWG} = 8, all ONUs can share approximately 7 wavelengths for bandwidth-shared services.

5. Conclusion

We have proposed optical access architecture designs based on WDM-direct toward new-generation networks for each of the two types of topologies: SS and PDS. Our proposed architecture can provide not only conventional bandwidth-shared services (e.g. current Internet services) but also bandwidth-guaranteed services which require more than 10 Gbps-bandwidth and QoS guarantee by end-to-end lightpaths directly established to each ONU.

Firstly, we have shown designs of SS-type new-generation optical access architecture, and have established the experimental setup of the system using 3 wavelengths. As a result of experimental demonstration, we confirmed that the OLT successfully switches between packet/lightpath data transmissions (i.e. bandwidth-shared/bandwidth-guaranteed services) for each ONU. In addition, without optical amplifiers, the system experiences the optical power loss ranging from −28.0 dB to −23.9 dB in each of upstream/downstream transmissions.

Secondly, we have shown designs of PDS-type new-generation optical access architecture, and have theoretically analyzed the maximum guaranteed bit-rate per ONU on end-to-end lightpaths and the average available number

of channels for bandwidth-shared services. We have shown that, when the number of ONUs is 8, 16, 32 and 64, the system numerically has the capacity for providing a *guaranteed/dedicated* bandwidth (i.e. end-to-end lightpaths) of 270, 130, 60 and 30 Gbps per ONU, and an additional *shared* bandwidth of less than 540, 260, 120 and 60 Gbps, respectively.

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