Application and Technical Issues of WDM-PON

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ABSTRACT

This paper reviews recent research activities on the applications and technical issues of WDM-PON. First, we describe two candidate applications of WDM-PON: one is a long-reach WDM-PON based on wavelength routing for metro/access integration, and the other is a short-reach WDM-PON for co-existence with current PON systems. We identify that the realization of colorless optical network units (ONUs) is an important technical issue for both applications, and an effective protection function is another important issue, especially for the long-reach WDM-PON. We introduce several 'colorless-ONU' approaches as well as introduce our recent research results to resolve the issues raised by some colorless-ONU approaches. In the second half of this paper, we describe two application: one is the wide-area optical/wireless hybrid access network based on long-reach WDM-PON with loop-back type colorless ONUs, and the other is the optical and wireless access based on short-reach WDM-PON coexisting with a current PON infrastructure with tunable-type colorless ONUs.

Keywords: Wavelength division multiplexing (WDM), Passive optical network (PON), WDM-PON, Radio-on-Fiber (RoF), Colorless optical network unit (ONU)

1. INTRODUCTION

The recent explosive growth of the Internet has triggered the introduction of a broadband access network based on fiber-to-the-office (FTTO) and fiber-to-the-home (FTTH). This trend will dramatically accelerate from now due to further progress in and adoption of contents delivery, TV telephony, and IP-TV services. To deal with the various demands, access and metro networks must be scalable in terms of capacity and accommodation, and flexible with regard to physical topology [1].

Figure 1 shows the transmission speeds of core and access networks over time. The transmission speed of optical access has increased by around 100 times in the last decade. In order to accommodate the huge traffic from the broadband access networks, the transmission capacities of core networks are being dramatically accelerated with the use of time-division multiplexing (TDM) and wavelength-division multiplexing (WDM) technologies; so that the total transmission capacity of WDM can reach up to 3 Tbps (40 Gbps x 80 wavelengths). As for the wireless access, the transmission speeds have also increased more than 100Mbps with wireless LAN (IEEE 802.11n), and dramatically accelerated up to 100Mbps mobile access with the Long Term Evolution (LTE). Japanese cell-phone company announced to start the LTE service in 2010, if all goes smoothly. We have been challenging the broadband mobile access beyond 100Mbps with the 4G mobile standardization.

The most traditional optical multiple-access technology is time-division multiplexed access (TDMA) and TDM-based optical access networks have been deployed widely. In current TDMA optical networks, total bandwidth of around one gigabit is shared by several tens of users via an optical power splitter [2]. In Japan, the full-scale introduction of GE-PON systems has been started, and the number of FTTH subscribers exceeded 15 million in 2009.

As the latest trend in standardization activities on the next generation optical access, IEEE started developing the standard of 10 Gb/s Ethernet Passive Optical Network (10G-EPON) in P802.3av Task Force in 2006; completion of its work is expected by 2009 [3]. The FSAN (full service access network) forum, which submitted B-PON and G-PON proposals to ITU-T, is studying various technologies and architecture options for next generation optical access systems (e.g. WDM, 10 Gbit/s and increased reach/split) and how an operator would evolve from a deployed ITU-T G-PON (or IEEE GE-PON) to a next generation access system. [4].

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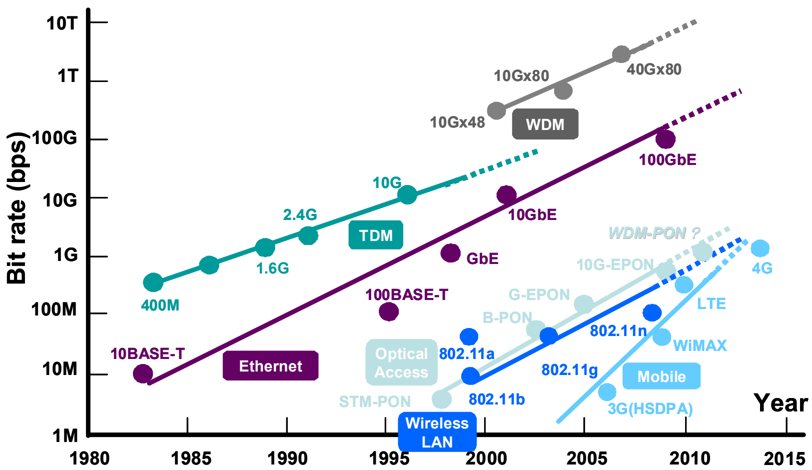


Figure 1. Transmission speeds of core and access networks.

The further enhancement of TDM access technologies beyond ten gigabits is facing various barriers to cost-effective realization: the history of the core network has proven this. In addition, a higher-speed TDMA requires higher-rate burst-mode circuits. Given this, one of the most attractive candidates for future optical access next to 10G-EPON and 10G-PON is WDM-PON, in which each signal from/to each user occupies a different wavelength. WDM-PON is a physically shared system, but a logically unshared system. This provides certain advantages as follows.

1. The bandwidth for each user can be easily upgraded.

2. Various services can be provided per wavelength.

From the viewpoint of advantage 2, convergence with optical and wireless access will flexibly provide broadband services in future access networks. Recent proposals establish to provide wireless and/or wired services over WDM-PON [5]-[8]

This paper reviews the technical issues of WDM-PON, some solutions, and their applications to simultaneously achieve optical and wireless access on the same platform. Section 2 describes our focus on two candidate applications of WDM-PON: one is a long-reach WDM-PON based on wavelength router for metro/access integration, and the other is a short-reach WDM-PON co-existing with current PON systems. We identify that the realization of colorless optical network units (ONUs) is an important technical issue for both applications, and an effective protection function is another important issue, especially for the long-reach WDM-PON. Next, we review several 'colorless-ONU' approaches as well as address several issues raised by some colorless ONU approaches. We also describe a long-reach WDM-PON architecture with a wavelength shifted protection scheme as well as loop back type colorless ONUs. In Section 3, we show a hybrid optical/wireless wide-area access network based on long-reach WDM-PON architecture. Section 4 describes another architecture to provide wired and wireless services based on a short-reach WDM-PON that coexists with a current PON system.

2. TECHNICAL ISSUES OF WDM-PON

Figure 2 summarizes the application and technical issues for two options to implement WDM-PON: one is to use wavelength routers and the other is to use power splitters in the optical distribution networks (ODNs). The wavelength-router-based WDM-PON, where wavelength allocation is basically static, is applicable to short-reach access for green field and long-reach access due to the low loss-budgets of the wavelength routers. The power-splitter-based WDM-PON is applicable to migration scenarios from legacy PONs, since they use the same ODNs as the existing infrastructure. Here, dynamic wavelength allocation is possible [9], because the power splitters are transparent to wavelength. The researches of WDM-PON are mainly focused on two applications: one is a long-reach WDM-PON based on wavelength routing for metro/access integration, and the other is a short-reach WDM-PON for co-existence with current PON systems.

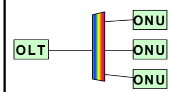
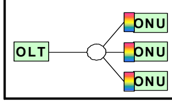
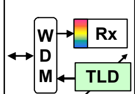
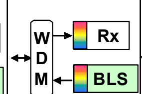
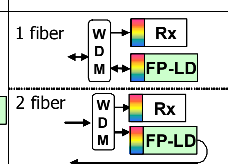
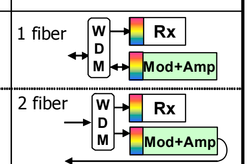
	Application	Issue	Note
Wavelength-router-based WDM-PON 	• Long reach (metro/access integration) • Short reach (last one mile) for green field	• Colorless ONU • Protection for long reach	• Wavelength allocation is basically static.
Power-splitter-based WDM-PON 	• Short reach (last one mile) for migration from legacy PONs	• Colorless ONU	• Dynamic wavelength allocation is possible [9].

Figure 2. Applications and technical issues for two types of WDM-PON.

The common technical issue in both types of WDM-PON is the colorless ONU; the ONUs should be colorless (in other words, no ONU is wavelength specific) to reduce the costs of operation, administration, and maintenance (OA&M) functions, as well as the production cost, since mass production becomes possible with just one specification. Another issue, especially for the long-reach WDM-PON, is a protection function that can counter feeder fiber breaks. The rest of this section describes the various colorless-ONU techniques and the protection function for the long-reach WDM-PON.

Many colorless proposals have been reported [10]–[18]. The proposals can be summarized into two main schemes as shown in Fig.3: local emission and wavelength supply. In the case of the power-splitter-based WDM-PON, wavelength selectors (WSs) are needed. Note that no WSs are needed in the case of the wavelength-router-based WDM-PON, because the wavelength from/to each ONU is selected by the wavelength-router. We select the colorless ONU scheme suitable for the application shown in Fig.2. Enabling technologies for the two schemes are described in this section.

	Local emission		**Wavelength supply**	
	Wavelength tuning	Spectrum slicing	Injection locking	Loop back
ONU configuration				
Number of fibers	1	1	1 or 2	1 or 2
Coherency of upstream-signal light	Coherent	Incoherent	Depends on the locking condition and the type of seed light	Depends on the type of seed light
Typical transmission rate	~10 Gbps or over	~2.5 Gbps (~10 Gbps with FEC [12])	<1 Gbps (ASE-seeded/1-fiber)	~1 Gbps (ASE-seeded/1-fiber/direct-mod) ~10 Gbps (LD-seeded/2-fiber/ext-mod)
Technical issues	Low-cost implementation	Beat noise of BLS	•Back reflection •SNR of seed light •Insufficient locking [14],[15]	•Back reflection •SNR of seed light
Wavelength control at ONU	In the case of power-splitter-based WDM-PON, the wavelength control of TLD and wavelength selectors are needed. In the case of wavelength-router-based WDM-PON, no wavelength selectors are needed, and thus only the wavelength control of TLD is needed.			

TLD: Tunable laser diode, BLS: Broadband light source, Rx: Receiver :Wavelength selector (WS)
Mod: Modulator, Amp: Optical amplifier

Figure 3. Approaches to realize colorless ONUs. FEC; forward error correction; FP-LD; Fabry–Perot laser diode; ASE, amplified spontaneous emission; SNR; signal-to-noise ratio.

2.1 Local emission scheme

There are two local emission approaches: a wavelength tuning [10] and spectrum slicing [11], [12]. The ONU of the wavelength tuning approach consists of a tunable laser diode (TLD) as a transmitter (Tx), an optical receiver (Rx) with WS, and a WDM coupler that divides/combines the upstream and downstream signals. The wavelength-tunable scheme is expected to achieve a large loss budget and high speed operation at 10 Gbps, because a coherent light is used. To achieve Tx and Rx tunability with ease for WDM-PONs based on the power-splitter, a tunable fiber ring laser is another option, where the wavelength selector might be simultaneously used for selecting the downstream wavelength. We have reported the feasibility of the fiber ring laser using a semiconductor optical amplifier (SOA) and an optical tunable filter (OTF), which operated over a 20-nm wavelength range with accuracy of +/- 1.75 GHz [19].

The configuration of the ONU in the spectrum slicing approach is similar to that in the wavelength tuning approach except that a broadband light source (BLS) with WS is used instead of the TLD. The advantage of the spectrum slicing approach in wavelength-router-based WDM-PONs is its light sources, e.g. superluminescent diodes (SLDs) under quasi-athermal operation without precise wavelength control can be used. A particular noise factor in the spectrum slicing approach is the signal-signal beat noise. The signal-to-noise ratio (SNR) of the signal-signal beat noise can be expressed as being proportional to the ratio of the data rate to sliced bandwidth [12]. To realize high speed operation, broadening the sliced bandwidth is inevitable; it follows that the number of available channels decreases assuming the light source has a fixed bandwidth. Broadening the sliced bandwidth also increases the fiber dispersion penalty. The use of forward error correction (FEC) can effectively overcome this drawback. The 10-Gb/s, eight channel spectrum-sliced DWDM transmission with the channel spacing of 200 GHz was confirmed through the use of FEC [12].

2.2 Wavelength supply scheme

There are two approaches to wavelength supply scheme: injection locking [13]-[15] and loop back approach [16]-[18]. In the injection locking approach, the ONU consists of a Fabry-Perot laser diode (FP-LD) as the Tx, an Rx with WS, and a WDM coupler that divides/combines the upstream and downstream signals and/or the injection light. The spectrum sliced light or laser light is injected into the FP-LD, so as to lock the wavelength of the upstream signal. The relative intensity noise (RIN) of the upstream signal (injection locked light) depends on the injection locking condition [14], [15].

In the loop back approach, the ONU consists of an optical modulator (Mod) and optical amplifier (Amp) as the Tx, an Rx with WS, and a WDM coupler that divides/combines the upstream and downstream signals and/or continuous wave (CW) light. The CW light supplied from the OLT is modulated and amplified by the Mod and Amp, respectively, to generate the upstream signal.

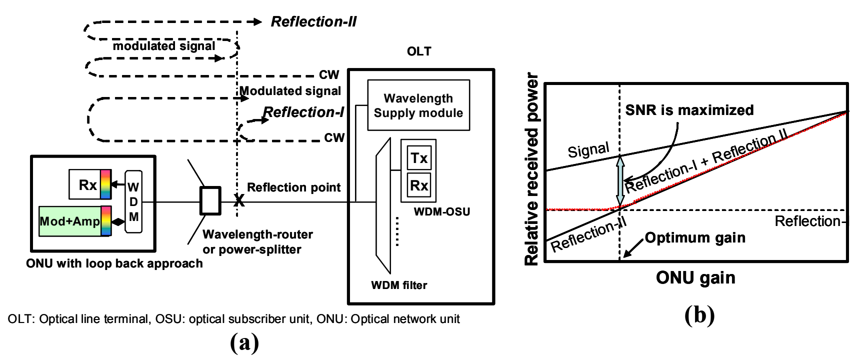


Figure 4. Impact of back reflection in loop back approach with one fiber configuration. (a) Path of two back reflection light, (b) Increase in the impact of Reflection-II with ONU gain.

To avoid the degradation due to back reflection of the upstream signal, one option is to base wavelength supply on the two-fiber configuration; the long-reach WDM-PON described in Section 3 assumes this configuration. In the one-fiber configuration, two types of back reflection, the back reflection of continuous wave (CW) light from the OLT (reflection I) and that of the modulated signal from the ONU (reflection II), as shown in Fig.4(a), must be considered, because the interference between the signal and back reflection degrades the received SNR due to intensity noise [20]. The impact of reflection-II increases strongly with ONU gain, so that the received SNR falls as ONU gain is increased, as shown in Fig.4(b) [20]. To reduce the impact of reflection-II, we employ a gain-saturated SOA in the ONU [21].

2.3 Protection function

In the long-reach WDM-PON, the failure of the feeder fiber carrying the WDM signals may cause the loss of data for all users. Thus, a protection function for the feeder fiber is required to realize the reliable WDM-PON. Several approaches have been proposed to achieve the protection needed [22]–[24]; they use 3-dB optical couplers to split (or combine) the path of WDM signals to/from both the working and protection fibers in the OLT or in the wavelength router. Note that the OLT and the wavelength router are typically located in the central office (CO) and in the access node (AN), respectively. This protection scheme, unfortunately, has a low loss budget, because of the use of the 3-dB optical couplers [22]-[24]. To address this issue, we have proposed and demonstrated a wavelength-shifted protection scheme utilizing the cyclic property of the 2×N athermal arrayed-waveguide grating (AWG) and two wavelength allocations, one each for working and protection, that does not use 3-dB optical couplers for protection [25]. While this protection scheme can be applied to WDM-PONs with various types of colorless ONU, the loop-back approach is the most suitable choice because we do not need any protection function in the ONUs.

3. LONG-REACH WDM-PON

3.1 Optical/wireless hybrid wide-area access network

The growth of e-businesses is accelerating strong demands for broadband services over gigabit, for business users. Such business users need wide-area broadband access networks that offer high-speed connection services between several local area networks [16]. The long-reach WDM-PON promises a wide-area access network that realizes consolidated operation to reduce OA&M cost, because it can offer from gigabit to ten gigabit-class guaranteed-bandwidth services according to user demand.

Figure 5 illustrates the optical/wireless hybrid wide-area access network based on long-reach WDM-PON [26]. OLTs and an optical carrier supply module (OCSM) are located in the center node; the OCSM is an optical frequency comb generator that supplies multi-wavelength carriers to several OLTs. The OLT has interfaces for radio-on-fiber access (RoF IFs) as well as those for high speed optical access such as 10 Gigabit Ethernet (10GE IFs). The RoF approach simplifies the system architecture by directly delivering broadband signals of radio frequency through optical fibers.

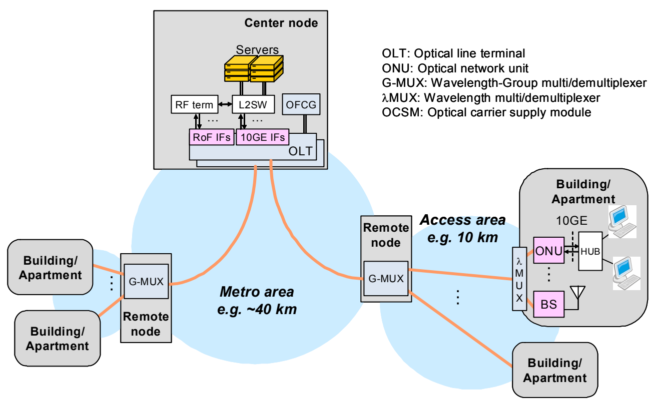


Figure 5. Optical/wireless hybrid wide-area access network.

One of the most attractive RoF approaches over 100Mbps with the millimeter band is to heterodyne two optical frequencies whose difference corresponds to the radio frequency (RF), e.g. 60 GHz [27]. By modulating one of two optical frequencies before fiber transmission, the RF signal can be extracted by heterodyne detection after fiber transmission. This approach can eliminate not only the local RF generator in each base station (BS), but also achieve better fiber-transmission performance than sub-carrier modulation (SCM) approach due to the fiber dispersion. However, the two optical frequencies must be precisely controlled to generate a stable RF signal after detection. The OCSM that can inherently provide such precise frequency control between any two wavelengths are an attractive candidate for this purpose as well as for multiplexing many different RF signals.

This network uses DWDM wavelength channels (e.g. 64 channels) and the group multi/demultiplexer (G-MUX) in each remote node divides/combines the DWDM channels into/from several groups of wavelengths (e.g. 8 wavelengths x 8 groups). Each wavelength group is dedicated to a building/apartment, where a wavelength pair can provide either optical access via an ONU or RoF access with a BS (e.g. 1 x 10GE-ONU and 3 x RoF BSs in each building/apartment).

3.2 System Configuration of wide-area optical/wireless hybrid access network

Figures 6(a) and (b) show the configuration and optical spectrum of the OCSM that we reported previously [28]. By modulating the CW lights of seed laser diodes (LDs λ1 to λn in the figure) with a phase modulator (PM) and an intensity modulator (IM) using 25-GHz radio frequencies with appropriate amplitudes, we can obtain multi-wavelength optical carriers as the modulation sideband as shown in Fig. 6(b); the spectrum consists of four wavelength groups where each group consists of eight wavelengths with 25-GHz spacing. Typically, low-cost optical filters for group multi/demultiplexing require an adequate guard-band between neighboring groups. As shown in the spectrum, this OCSM is very suitable for such a group multi/demultiplexing because one can easily adjust the spacing between neighboring wavelength groups by adjusting the seed wavelengths.

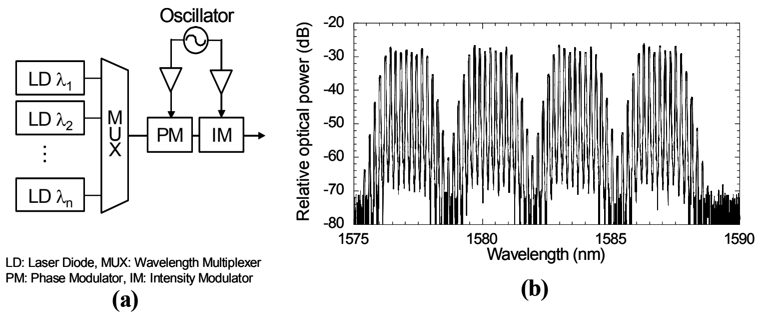


Figure 6. (a) Configuration and (b) optical spectrum of optical carrier supply module (OCSM).

Figure 7 shows a detailed configuration of the proposed network system. Wavelength pairs to be used for an ONU or a BS are $\lambda_{k1}/\lambda_{k3}$, $\lambda_{k2}/\lambda_{k4}$, $\lambda_{k5}/\lambda_{k7}$, $\lambda_{k6}/\lambda_{k8}$ where k is the group number (k = 1 ~ n). In the case of the OCSM shown in Fig. 7(b), n is 4; we can increase n by adding seed wavelengths to OCSM. The center node consists of n sets of modulation arrays (Mod array), n sets of receiver arrays (Rec array) and group multi/demultiplexers (G-MUX/G-DMX). Each Mod array multi/demultiplexes the eight wavelengths in each group by using arrayed-waveguide gratings (AWGs), and λ_{k1}, λ_{k2}, λ_{k5}, λ_{k6} are modulated by 10Gbit/s binary NRZ data (for optical access) or 10GHz-band IF data (for RoF access). In the remote node, the G-MUX/DMX divides/combines signals by wavelength groups. In the building, AWGs multi/demultiplex the eight wavelengths. The BS receives the RoF signal by heterodyning the wavelength pair (e.g. $\lambda_{k1}/\lambda_{k3}$) to generate a wireless signal with 60-GHz RF as well as transmitting the RoF signal by remotely modulating and transmitting one of the wavelength pairs (e.g. λ_{k3}) upstream [29]. The ONU simply receives one modulated wavelength pair (e.g. λ_{k2}) as well as modulating/demodulating another wavelength pair (e.g. λ_{k4}). Figure 8 summaries the signal spectra of OLT, ONU, and OLT. By using this system configuration, we can realize a wide-area access network that provides both high-speed optical access and fiber-wireless access flexibly depending on need.

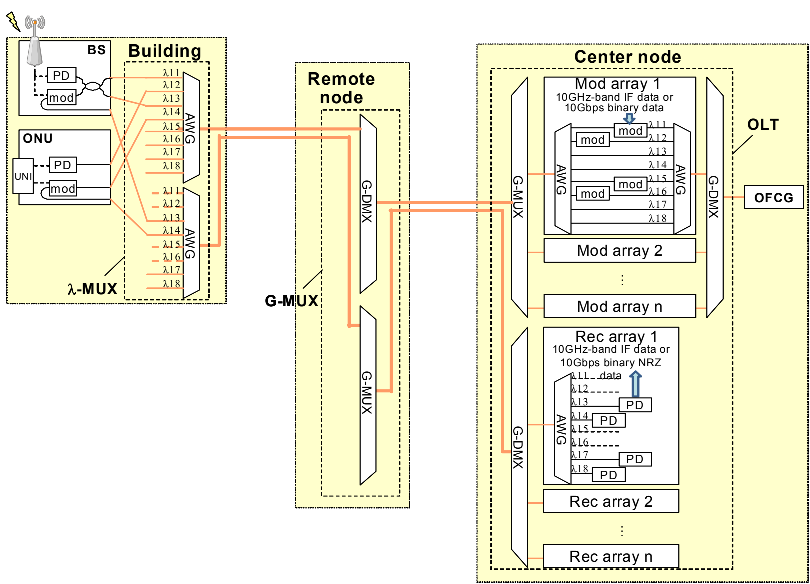


Figure 7. System configuration of optical/wireless hybrid wide-area access network.

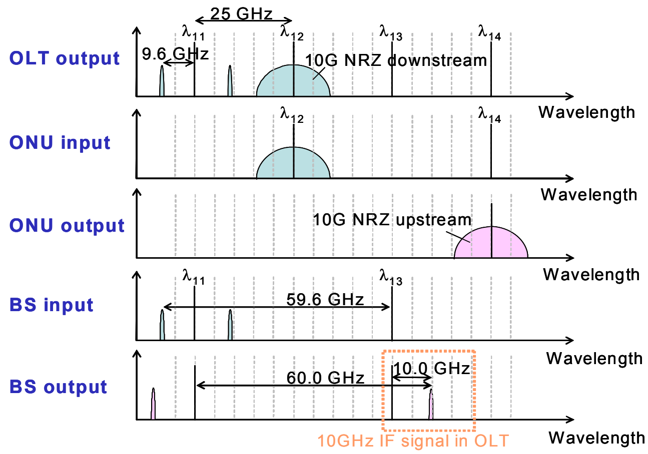


Figure 8. Signal spectra of OLT, ONU and BS.

4. SHORT-REACH WDM-PON CO-EXISTING WITH CURRENT PON SYSTEM

Figure 9 illustrates the migration to WDM-PON, that accommodate wired and wireless services, from the current PON system via the common power-splitter-based ODN. The WDM-OLT and the WDM-ONU in Fig. 9 for WDM-PON can be simply added without changing the ODN: the WDM-OLT comprises multiple optical subscriber units (OSU), each of which communicates with a WDM-ONU. The detailed wavelength allocation is also shown in Fig. 9. According to the standardization bodies, the upstream and downstream wavelengths of the current PON systems range from 1260 to 1360 nm and from 1480 to 1500 nm, respectively. The wavelengths for video use lie in the range of 1550 to 1560 nm. The simplest approach to wavelength

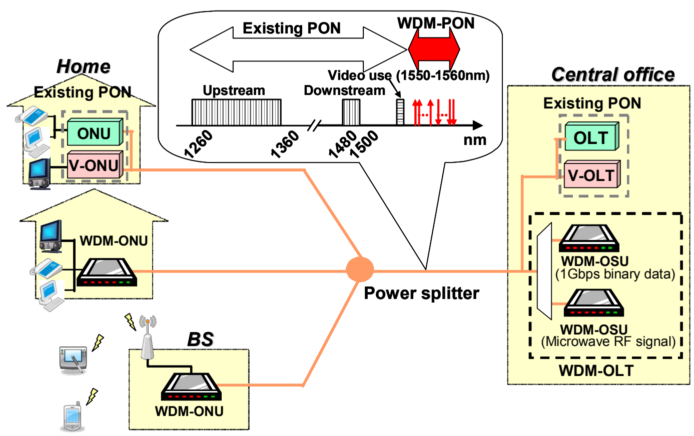


Figure 9. Migration to WDM-PON from current PON system over power-splitter-based optical distribution network (ODN).

allocation for WDM-PON is to use the L band, which is located in the wavelength region that is longer than that reserved for video use. On the assumption that many wavelengths will be needed to accommodate a large number of users, DWDM technologies will play an important role in efficiently utilizing the limited wavelength region available.

To construct an easy to use power-splitter-based WDM-PON for mass users, plug-and-play functionality is essential [10]. Plug-and-play means automatic wavelength control of the ONU, which is as critical as the precise time control needed in the current PON based on TDMA.

We demonstrated wavelength-tuning colorless ONUs with the plug-and play function [10], from the viewpoint of realizing the transmitter without WS. Wavelength control can be achieved with initial wavelength setting and wavelength stabilization. The former remotely and automatically establishes the initial wavelengths between each ONU and the OLT. After the initial wavelength is set, wavelength stabilization is carried out. This is especially critical if the channel spacing is narrow, and thus the multiwavelength monitoring technique [30] is required.

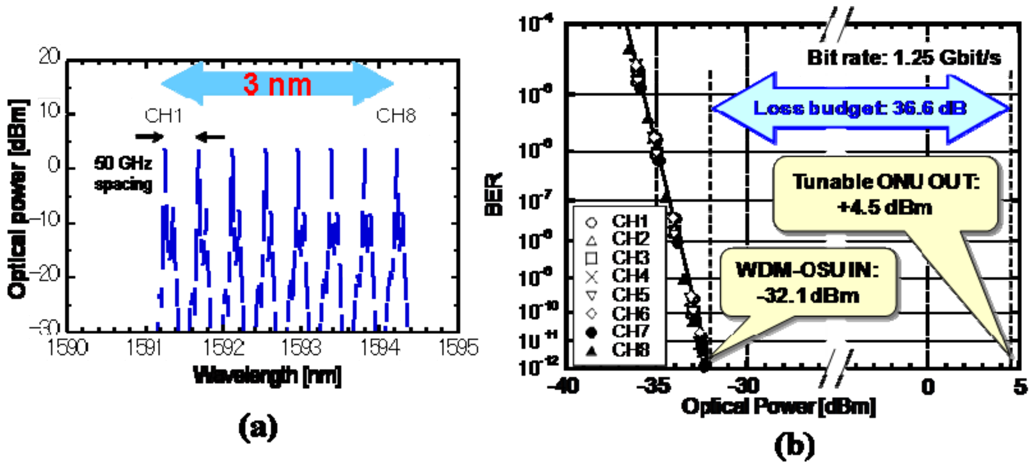


Figure 10. Performance of the colorless ONU with tunable DWDM-SFP for the WDM-PON co-existing with a legacy PON, (a) optical spectra, (b) loss budget.

Figures 10(a) and (b) show the optical spectra and loss budget of the colorless ONU based on a SFP (Small Form-Factor Pluggable) for the WDM-PON that can co-exist with a legacy PON [31]. The DFB-LDs in SFPs are directly modulated with 1.25Gbps binary data. The 3-nm tunable range, which provides 8 channels with 50 GHz spacing, was verified in [29]: wavelength tuning was realized via temperature control of the laser in the SFP. The loss budget between the WDM-OSU and colorless ONU (WDM-ONU in Fig. 9) was reported in [30] as over 36 dB, which is sufficient to support the adoption of legacy ODNs. To provide wireless services with microwave band simultaneously over the WDM-PON, RoF techniques [6], [32] are available to directly modulate the DFB-LD in SFP with microwave band RF signals.

5. SUMMARY

We have described the technical issues, solutions, and applications of WDM-PON. The WDM-PON can construct scalable and flexible networks to provide wireless and/or wired services, so it is the leading candidate for the next generation optical access systems beyond 10 Gbps TDMA systems. The main technical issue of WDM-PON was how to realize the colorless ONU. Two candidates, local emission and wavelength supply, were summarized and their features were explained in detail. The requirements and technical issues related to the protection function for the feeder fibers of WDM-PON were elucidated. We described the two main applications of WDM-PONs: long-reach WDM-PON and short-reach WDM-PON that co-exists with a current PON system. The former offers wide-area broadband optical/wireless hybrid access networks that can accommodate the large number of business users expected. The latter enables migration from the current PON systems by utilizing the current infrastructure. The requirements and technical issues associated with the plug-and-play function, which remotely and automatically establishes the initial wavelengths of each ONU, were discussed. The wireless services can be also accommodated with the short-reach WDM-PON utilizing the microwave band RoF techniques.

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