Any-Double-Link Failure Tolerant Bypass/Backup Switchable WDM-PON Employing Path-Pair Shared Protection and Bidirectional Wavelength Pre-assignment

Takahiro Kodama[1,2], Tomoya Nakagawa[1], and Ryosuke Matsumoto[2]

1. Faculty of Engineering and Design, Kagawa University, 2217-20 Hayashi-cho, Takamatsu, Kagawa 761-0396, Japan

2. National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8568, Japan

kodama.takahiro@kagawa-u.ac.jp

Abstract: We propose two-of-four long-link failure tolerant path-pair shared protection and bi-directional wavelength pre-assignment for robust bypass/backup-path switchable wavelength-division multiplexing based coherent optical access network systems that experimentally achieve < 2-dB penalty for any double-link failure. © 2022 Authors

1. Introduction

After the 5G era, a beyond-100-G-class optical access network (OAN) system will be required to connect wireless base stations and optical aggregation stations [1]. The application of coherent technology has been investigated to handle efficiently a transmission capacity of 100 Gb/s/λ [2-4]. There are two topologies for OANs: a single-star topology comprising a dedicated link-oriented architecture and a passive double-star topology comprising a shared link-oriented architecture. The dedicated link-oriented architecture is suitable for an OAN system that accommodates radio base station traffic, which requires low latency with uncomplicated access control. The shared link-oriented architecture is characterized by high branch loss, but yields a high economic benefit because one trunk fiber accommodates multiple radio base stations [5]. Both the general single-star and passive double-star topology configurations have no secondary links, so they are vulnerable to failures of the dedicated primary (DP) link or shared primary (SP) link in the event of a disaster. Therefore, a disaster resistant OAN architecture is required to deal with primary link disconnections. Previous research has aided in standardizing several protection methods and has led to the development of reconnection functions for passive double-star topologies [6]. A Type A topology with 1+1 protection, which is described in Section 2, reinforces the SP link similar to a passive double-star topology that adds a feeder fiber for the dedicated secondary (DS) link between the output terminal of an 1×2 optical coupler of a remote node and an additional 1×2 optical switch. However, let us consider a case where either the SP link or the shared secondary (SS) link is disconnected. Then, a colorless function is required to switch wavelength path groups to avoid wavelength collision and reflection between the uplink and downlink [7]. A switchable coherent wavelength division multiplexing (WDM)- passive optical network (PON) system was recently proposed that switches a DP link that acts as a bypass to an SS link that acts as a backup path [8]. It has been shown that reconnection is possible by using both this function to switch to the SS link and the colorless function when one of two DP links is broken. However, since there is only one SS link, the architecture in [8] could not be reconnected using the route switching function or the colorless function when DP-DP or DP-SS links are broken.

This paper proposes a novel reconnectable path-pair shared protection scheme incorporating a full-terminal-connected 2×2 optical coupler in the remote node and a shared link switchable 2×2 optical switch in the optical line terminal (OLT) that can deal with any double-link failure occurring simultaneously. When the dedicated and shared links are simultaneously broken, reconnection using the economical SS link and cross-wavelength allocation between the two DP links are performed to prevent end-face reflections due to link failures. In addition, the proposed bidirectional backup wavelength pre-allocation reduces the wavelength switching time using one set of transmitter (Tx) and receiver (Rx) light sources on the optical network unit (ONU) side, and minimizes the use of Tx and Rx light sources on the OLT side. We conduct a 4λ×100 Gb/s/λ/way full-duplex transmission experiment on a 400-G OAN, and confirm the feasibility of the proposed bypass/backup switchable coherent OAN architecture suffering a double-link failure. The difference from the previous research is that our proposed protection and pre-wavelength assignment is for any double link failure in the event of a large-scale disaster.

2. Comparison of Protection Schemes in Bypass/Backup Switchable PON Architecture

Here, we compare three protection methods with additional links for a WDM-PON with four ONUs. Figure 1(a) shows an architecture in which Type A protection is applied to each shared link in a half-split PON. Figure 1(b) shows an architecture in which shared protection is applied by adding an SS link to a half-split PON. Figure 1(c) shows an architecture in which path-pair shared protection is applied by adding two SS links to a half-split PON.

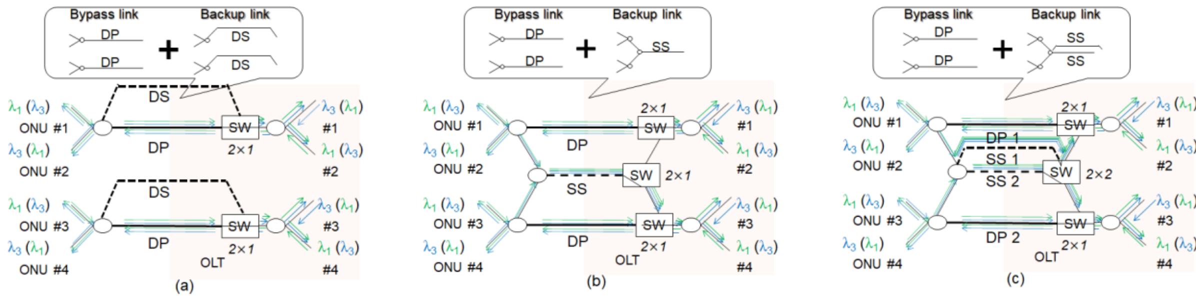

Fig. 1. Protection architectures and initial λ-link assignment: (a) 1+1 for half-split NW, (b) shared with single path, (c) shared with path pair.

Table 1. Reconnection Ability from Double Link

Architecture \ Link-failure pattern	SS&SP	DS&DP	DS&DS	DP&DP	DP&SS	SS&SS
1+1 for half-split PON (Type A)		Impossible	Possible	Possible		
Shared with single-path [8]				Impossible	Impossible	
Shared with path-pair				Possible	Possible	Possible

Table 2. Wavelength Values

	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8
Wavelength [nm]	1550.5	1550.9	1551.3	1551.7	1552.1	1552.5	1552.9	1553.3

Table 3. Backup Wavelength Pre-assignment

	Uplink				Downlink			
	ONU #1	ONU #2	ONU #3	ONU #4	ONU #1	ONU #2	ONU #3	ONU #4
No failure	λ_1	λ_3	λ_1	λ_3	λ_3	λ_1	λ_3	λ_1
DP	λ_1	λ_3	λ_2	λ_4	λ_3	λ_1	λ_4	λ_2
SS	λ_1	λ_3	λ_1	λ_3	λ_4	λ_2	λ_4	λ_2
DP-DP	λ_1	λ_3	λ_2	λ_4	λ_4	λ_2	λ_3	λ_1
SS-SS	λ_1	λ_3	λ_1	λ_3	λ_4	λ_2	λ_4	λ_2
DP-SS	λ_1	λ_3	λ_2	λ_4	λ_7	λ_5	λ_8	λ_6

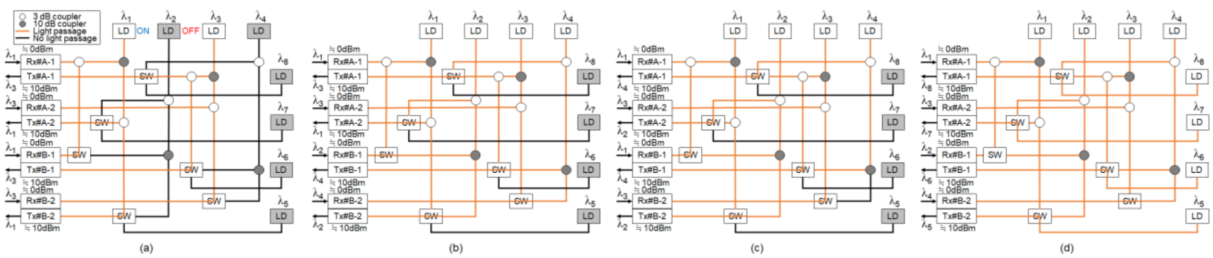

Fig. 2. OLT-side LD commonization setup: (a) no failure case, (b) DP-DP failure case, (c) SS-SS failure case, and (d) DP-SS failure case.

First, we discuss the link-failure tolerance in the four architectures. Any of the configurations can handle any single-link failure. However after a double-link failure, whether or not it is possible to reconnect the path depends on the architecture. Table 1 summarizes the potential reconnections for double-link failure patterns. In the configurations shown in Fig. 1(b), neither path can be reconnected because the number of remaining links is less than the number of failed links. In the configuration shown in Fig. 1(a), the path cannot be reconnected if a double-link failure occurs in the same PON after splitting. However, the path can still be reconnected if the links involved in the double-link failure are disconnected. The configuration shown in Fig. 1(c) is the most robust protection architecture because the path can be reconnected even if one double-link failure occurs.

Tables 2 and 3 summarize the wavelength value and bidirectional backup wavelength pre-assignment, respectively. Backup wavelength pre-assignment and route switching before and after the occurrence of a link failure are examined. The important point is to operate the entire uplink and downlink system with as few wavelengths and wavelength-shift values as possible while avoiding reflections. The assignment rules must be satisfied in the following order:

(i) To suppress the influence of near-end reflection, different wavelengths are assigned to each ONU for transmission and reception regardless of before or after the link failure.

(ii) If the shared link fails, the occupied link will continue to be used without being affected by reflection from the shared link due to the wavelength allocation in (i).

(iii) In the event of an exclusive link failure, it is necessary to use a shared link, so the ONU group (#1 and #2) and the ONU group (#3 and #4) must be assigned independent wavelengths.

(iv) When the occupied link and shared link fail at the same time, it is necessary to consider (ii) and (iii) at the same time, and the wavelength allocation must be independent for the uplink and the downlink.

Figure 2(a) shows an OLT-side laser diode (LD) wiring structure that allows two LDs to be shared between two PONs for an upstream/downstream transmission in a switchable PON without link failures. With this switch setting, a power-saving operation can be performed in which two of the eight LDs are in sleep mode. Figures 2(b)-2(d) show OLT-side LD wiring structures that operate all eight LDs between two PONs for upstream/downstream transmission in a switchable PON with a double-link failure.

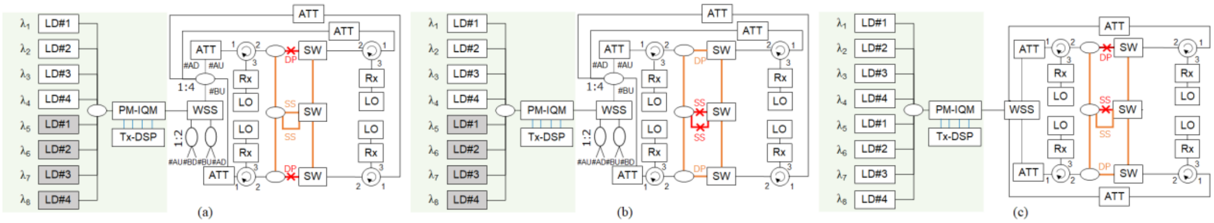

Fig. 3 Experimental configuration for double link failure: (a) DP-DP failure case, (b) SS-SS failure case, and (c) DP-SS failure case.

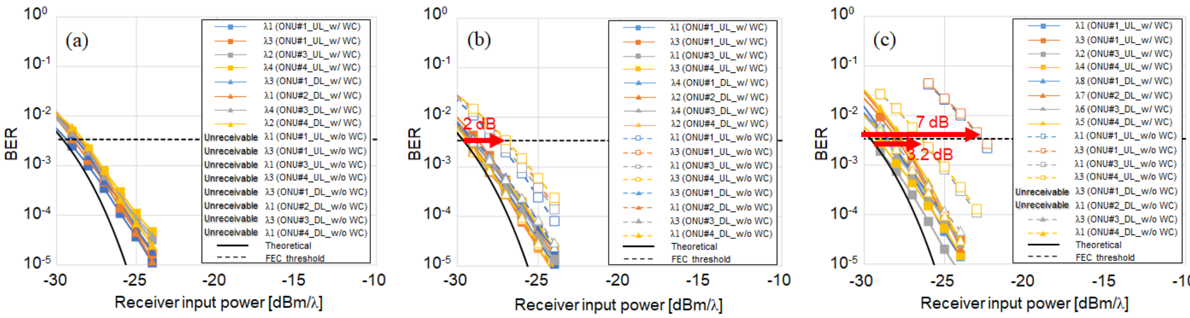

Fig. 4 Experimental BERs: (a) DP-DP failure case, (b) SS-SS failure case, and (c) DP-SS failure case.

3. Experiment on Path-Pair Shared Protection for Double-Link Failure

We performed no-link failure and double-link failure experiments on a coherent WDM-PON system with protection, as shown in Fig. 3. The uplink/downlink transmission signal is a 4λ×100-Gb/s polarization-multiplexed (PM) quadrature phase-shift keying signal with a 50-GHz channel spacing. In this emulation, a full-duplex transmission is performed on the primary and secondary links, and upstream and downstream static characteristics are evaluated when wavelength conversion (WC) and path switching are performed before and after a double-link failure. By physically exposing the connecting end faces of the two patch cords to air, we emulate the Fresnel reflection caused by a fiber link failure. Attenuation of the received power, which changes with the transmission distance, is simulated by adjusting the input power to the trunk span using an optical attenuator. This method evaluates the pre-forward-error-correction (FEC) bit error ratio (BER) characteristics when only the signal power after passing through the trunk span is changed while maintaining a constant amount of reflected power because of the disconnection of the fiber link. The bundled WDM signals are split by a wavelength selective switch and combined using a coupler (CPL) to emulate full-duplex transmission and independent signal generation from different Txs.

A WDM signal generated by an optical Tx, including an LD-array, CPL-array, PM-IQ modulator, and real-time digital signal processor (DSP), is launched to a trunk span fiber corresponding to the primary or secondary link as an upstream signal and a downstream signal. On the Rx side of each ONU and OLT, the signal power is mixed with local oscillator (LO) light(s) and coherently detected. After extracting the desired wavelength components, the received WDM signal is BER reconstructed and measured using a real-time DSP.

Figure 4 shows the measured BER of all upstream and downstream ONU and OLT signals with and without double-link failures. Here, we associate a 7% hard-decision FEC threshold (3.4×10^{-3}) with achieving error-free operation. The power penalties in cases of a double-link failure before WC in the downlink for three failure cases, *i.e.*, DP-DP, SS-SS, and DP-SS failure cases, exceed 2 dB or the signals become unreceivable owing to the effect of back reflection. The power penalty in cases of a double-link failure after WC in the downlink for the three failure cases is less than 2 dB. Here, unreceivable means that the clock cannot be recovered from the received signal.

4. Conclusions

We proposed a bypass/backup switchable WDM-PON with path-pair shared protection and bidirectional backup pre-assignment for any double-link failure scenario. We experimentally confirmed that path reconnection is possible with minimal effects from end-face back reflection during a full-duplex transmission after switching and assignment.

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