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A Survivable Colorless Wavelength Division Multiplexed Passive Optical Network With Centrally Controlled Intelligent Protection Scheme

Min Zhu, Wen-De Zhong, and Shilin Xiao

Abstract—Several protection schemes have been proposed for wavelength division multiplexed passive optical networks (WDM-PONs). However, these existing schemes only work under the assumption that all the optical network units (ONUs) and the optical light terminal (OLT) continuously transmit optical signals. In practice, some ONUs may be in sleep mode to save power consumption or may be shut down whenever users are offline. Under such scenarios, the existing schemes would not work. To deal with more practical operation scenarios, we propose a centrally controlled intelligent protection scheme for survivable WDM-PONs, whereby the optical power on both the working and protection paths is monitored simultaneously, and the monitored results are fed to a novel logical decision unit which performs the protection switching. It provides 1:1 downstream protection and 1 + 1 upstream protection capabilities. The logic decision unit in conjunction with a power monitoring unit is implemented in the OLT to enable intelligent protection switching in more practical operation scenarios. Moreover, our proposed protection scheme can tell the connection status of every fiber path (working and protection), thus facilitating a faster failure recovery. The scheme feasibility is experimentally verified with 10 Gb/s downstream and 1.25 Gb/s upstream transmissions. The network performances in terms of complexity and availability are also evaluated.

Index Terms—Intelligent protection switching; Reflective semiconductor optical amplifier (RSOA); Wavelength division multiplexed passive optical network (WDM-PON).

I. INTRODUCTION

The wavelength division multiplexed passive optical network (WDM-PON) is a promising broadband access solution, because it offers huge bandwidth, protocol transparency, excellent security and easy upgradeability [1,2]. With the rapid increase of WDM-PON transmission capacity, any possible failure of either feeder fibers (FFs) or distribution fibers (DFs) will lead to a large amount of data loss [3]. Thus failure

monitoring and network protection are imperative for network operators to enhance the network survivability.

To date, several protection schemes for WDM-PONs have been reported based on simple power monitoring [4–10]. In [4,5], the periodic property of arrayed waveguide gratings (AWGs) is used to enable each DF to carry data traffic for more than one optical network unit (ONU), while ONUs are either adjacently connected to form a group [4] or connected in sequence to form a ring [5] to offer a backup protection path. In [6], both working FF and DF are duplicated for protection and connected to an $N \times N$ AWG located at the remote mode (RN). However, these distributed control schemes require optical switches (OSs) and monitoring units installed at each ONU to perform the protection switching, which increases the complexity and cost of ONUs. Although some centrally controlled protection schemes [7,8] have been proposed, they either require N OSs [7] or N electrical switches [8] in the optical light terminal (OLT), which increases the complexity. Compared with the schemes in [7,8], the protection schemes in [9,10] require only one OS located in the OLT, but only the DF [9] or the FF [10] is protected from fiber failure and thus the network availability is relatively low (refer to the network performance analysis in Section IV).

Moreover, and more importantly, all the existing protection schemes based on simple power monitoring [4–10] only work under the assumption that all the transmitters (TXs) in the ONUs and the OLT continuously transmit optical signals. However, in practice, (i) some TXs of ONUs or the OLT may frequently enter into sleep mode whenever there is no data to be sent in order to save power [11,12], (ii) some ONUs may be shut down whenever users are offline, and (iii) fiber faults may occur during the time when ONUs are offline or when ONUs are in sleep mode. In the above three cases, none of the existing protection schemes based on simple power monitoring [4–10] work. Specifically, for case (i) (or case (ii)) when an ONU is in sleep mode (or is offline), no optical signal is transmitted from that ONU. In such a case, if one of the previous schemes is employed, since no optical signal is received from that ONU, the corresponding power monitor in the OLT would assume that the working FF or the DF of that ONU is faulty and hence would trigger a false protection switching, resulting in a malfunction. In case (iii), if a fiber failure occurs in the working path of an ONU (e.g., the working DF fails) during the time when that ONU is offline or when that ONU is in sleep mode,

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the corresponding power monitor in the OLT cannot detect the recovery signal when that ONU wakes up (or is turned on). Hence that ONU would be treated as if it is still offline or in sleep mode, even though that ONU actually turns on its TX and transmits optical signal. Also in case (iii), if a fiber failure occurs in the protection path of an ONU (e.g., the protection DF fails), the corresponding power monitor in the OLT, which is designed to detect the upstream power in the working path only, would never know what happened in the protection path, so a hidden fiber failure would be left behind.

To deal with all the above scenarios for more practical operation, we here propose a centrally controlled intelligent protection scheme for survivable WDM-PONs with colorless ONUs, whereby the optical power on both the working and protection paths is monitored simultaneously. Note that, in the existing schemes, the optical power of the working path only is monitored without any intelligent decision. In our scheme, a novel logic decision unit in conjunction with a power monitoring unit is implemented in the OLT to enable the protection switching in more practical operation scenarios described above. By monitoring the optical power of each channel on both the working and protection paths, the proposed scheme can tell the connection status of both the working and protection paths of each channel, and hence can perform an effective protection switching with the aid of the proposed logic decision unit. Moreover, the detection results recorded by the power monitoring unit facilitate a faster failure recovery. The scheme feasibility is verified experimentally with 10 Gbit/s downstream and 1.25 Gbit/s upstream transmissions in Section III. The network performances in terms of complexity and availability are also evaluated in Section IV.

II. PROPOSED ARCHITECTURE AND OPERATION PRINCIPLE

The proposed centrally controlled self-protected WDM-PON architecture with N colorless ONUs is shown in Fig. 1. The OLT has three function units: transceiver unit, power monitoring unit and logic decision unit, which are interconnected to realize intelligent protection switching. The transceiver unit includes N transceivers, supporting N ONUs. In each transceiver, a TX generates a downstream signal and an optical circulator is used to separate down/upstream signals. Apart from receiving the upstream signal, an upstream receiver (RX) also acts as a monitor for monitoring the upstream power in the working path in the normal mode and generates an electrical signal to the logic decision unit upon detecting a drastic power loss. The wavelengths of all channels are multiplexed by a $1 \times N$ AWG at the OLT. The multiplexed signal is fed to port 1 of a 2×2 OS. Port 3 of the 2×2 OS is connected to another AWG with the same free spectral range (FSR) in the power monitoring unit. The power monitoring unit includes N power monitors for just monitoring the power of respective upstream signals on the protection path and generating respective electrical logic signals to the logic decision unit.

Ports 2 and 4 of the OS are connected respectively to the two $1 \times N$ AWGs with the same FSR at the RN, via two separate FFs (working and protection FFs). After being de-multiplexed

at the RN, each downstream signal is transmitted on one of the two alternate DFs (DF- i and DF- i^*), which are connected to the corresponding ONU- i . In each ONU, a 2×2 optical coupler (OC) is used to combine two DFs and to split the downstream optical power into two parts: one part is fed to a downstream receiver (RX); the other is amplified and re-modulated with upstream data via a reflective semiconductor optical amplifier (RSOA) operating in its gain-saturated region.

As shown in Fig. 1, the novel logic decision unit consists of N identical logic modules, each of which is related to a channel, and a multi-input-single-output logic OR gate. For each logic module, two input signals respectively come from the upstream RX and the monitor of the corresponding channel, and its output serves as one of the N input signals of the logic OR gate. The output of the logic OR gate controls the connection state (cross or bar) of the 2×2 OS. A single-link-failure scenario is assumed, because the chance of simultaneous multiple-link failures is negligibly small in an access network. Thus, when both the upstream RX and its associated monitor simultaneously experience a drastic power loss, it is assumed that the corresponding ONU either enters into sleep mode or is shut down. In such a case, no protection switching will take place. It is also noted that the proposed protection scheme can also protect against simultaneous multiple-link failures, except for a rare case where the two DFs for an ONU or the two FFs break down simultaneously. (In this rare case, that ONU or all the ONUs will completely lose the connection with the OLT, and hence any self-protection scheme would not work if no human intervention is involved.) Table I provides the decision states of the logic decision unit based on the logic inputs on both the working and protection paths of each channel.

In the normal working mode, the OS in the OLT is set to the bar state (i.e., 1-2 and 3-4 connection). Thus, a downstream signal is delivered only on the working path, consisting of the working FF and respective DF- i (red path). The downstream optical power is split into two parts by a 2×2 OC at each ONU, one of which is fed to a downstream RX; the other is amplified and re-modulated with upstream data via a gain-saturated RSOA. The upstream signal is split into two copies by the 2×2 OC, one of which transmitted in the working path is sent to the transceiver unit in the OLT; the other in the protection path is fed into the power monitoring unit. Hence, the WDM-PON can offer 1:1 downstream protection and 1 + 1 upstream protection capability.

In the case of any working DF failure, the corresponding upstream RX in the transceiver unit will detect the loss of that upstream signal, and hence a logic "0" signal will be generated to the logic decision unit. But, in this case, a monitor associated with the same channel in the power monitoring unit can detect light power, and a logic "1" signal will be generated. Consequently, the output of the logic decision unit will be a logic "1" signal, which triggers the 2×2 OS to the cross state (i.e., 1-4 and 3-2 connections) to set up the alternate (protection) path. Hence, all of the bidirectional transmissions are switched from the working path (red path) to the protection path (blue path). After protection switching, based on the detection results of the N monitors, the power monitoring unit can tell if it is a DF or FF failure in the working path; if it is a DF failure, it can also tell which DF fails. Thus, a fast failure restoration can be performed. In contrast, if an upstream RX

Fig. 1. (Color online) Schematic diagram of the proposed centrally controlled intelligent self-protected WDM-PON architecture.

TABLE I
TRUTH TABLE FOR THE DETECTION STATES OF THE UPSTREAM LIGHT ON BOTH WORKING AND PROTECTION PATHS OF EACH CHANNEL

Detection state of the upstream RX in the working path	Detection state of the monitor in the protection path	Output of the logic module for each channel
1 (with light)	1 (with light)	0 (normal working mode)
0 (no light)	1 (with light)	1 (do protection switching)
1 (with light)	0 (no light)	0 (no switching, but to repair protection fiber)
0 (no light)	0 (no light)	0 (ONU is in sleep mode or turned off)

detects the presence of light while its corresponding monitor detects no light, it indicates that the protection DF fails (and thus the network manager will be notified that the corresponding protection fiber link must be repaired in time), but in this case no protection switching will take place.

The logic expression of each logic module is $(\overline{w_i} \cdot p_i)$. If any of the above detection results occurs in all channels, it means the fiber failure takes place in either the working or protection FF. A logic OR gate is used to synthetically respond to the detection states from all N logic modules. Therefore, the logic expression of the output of the whole logic decision unit is

$$[(\overline{w_1} \cdot p_1) + (\overline{w_2} \cdot p_2) + \dots + (\overline{w_N} \cdot p_N)]. \quad (1)$$

The proposed WDM-PON can provide centrally controlled protection capability against the failures of both FFs and DFs. It should be mentioned that the proposed protection scheme is not restricted to a specific WDM-PON protection topology, and hence it is applicable to any protection topologies, including group protection [4], ring protection [5] and duplication protection [6].

As stated above, the upstream signal of any wavelength channel is always received by the corresponding transceiver in the OLT, while the corresponding power monitor in the OLT only needs to detect the presence (i.e., the power) of the upstream signal. Hence, there is no synchronization issue in receiving the upstream signal of each channel. On the

other hand, since the working path is geographically disjoint with the protection path, which may be much longer than the working path (depending on the fiber cable rollout), the fiber length difference (and thus the light propagation time difference) between the working path and the protection path may affect the decision results of the logic decision unit in some situations. Specifically, (i) when an ONU turns off its transceiver to enter into the sleep mode (or offline state) from the normal working state, or (ii) when an ONU turns on its transceiver to wake up from the sleep mode (or offline state), both the transceiver and the power monitor of the corresponding channel in the OLT would detect the power loss (or rise) in different times, respectively. Let us consider an upper-bound case in which the protection path is 20 km longer than the working path. Thus, in the normal working state, the transceiver can detect the power loss (or rise) by 0.1 ms ($=20 \text{ km}/(2 \times 10^5 \text{ km/s})$) earlier than the power monitor. Thus, when an ONU turns off its transceiver to enter into the sleep mode (or offline state) from the normal working state (i.e., case (i)), the logical signal "0" from the transceiver arrives at the logic decision unit by 0.1 ms earlier than the logical signal "1" from the power monitor. As a result, a logic "1" will be generated by the logic decision unit, which may trigger a false protection switching, resulting in a malfunction. However, in a practical system, the switching speed of the commercial opto-mechanical switch (e.g., the DiCon prism used in our experiment) or thermo-optical switch is about several milliseconds [13], which is much larger than

Fig. 3. (Color online) Measured BER of the DS and US signals at 1545.5 nm for different DS ERs. Insets show the eye patterns of DS and US signals when the DS ER is 5 dB.

US case the sensitivities in the working and protection paths were -29.4 dBm and -29.6 dBm, respectively. To investigate the power penalties, the BER performances of the back-to-back (BTB) case are also shown in Fig. 4. The power penalties between the BTB and the 20 km SMF transmission cases in the working path were about 0.7 dB and 2.3 dB for the DS and US transmissions, respectively. The power penalty for the DS transmission is mainly due to the chromatic dispersion, as the DS data rate is 10 Gbit/s, while the power penalty for the US transmission is attributed to the backscattering noise, since the upstream reuses the downstream wavelength.

Using the experimental setup, the fiber link (DF-1) between the AWG and the ONU-1 was intentionally disconnected to simulate the fiber cut scenario. Upon disconnecting DF-1, the US RX detected no optical power from the working path and hence generated a logic “0” signal ($w_1 = 0$), while the power monitor M_1 still detected optical power from the protection path and hence generated a logic “1” signal ($p_1 = 1$). As a result, the resultant output from the logic decision unit was a logic “1” signal ($\overline{w_1} \cdot p_1 = 1$), which activated the protection switching by changing the connection state of the 2×2 OS from its bar state (1–2 and 3–4 connections) to the cross state (1–4 and 3–2 connections) (please refer to Fig. 2). The protection switching time was measured to be 2 ms (see inset in Fig. 4), which is mainly determined by the switching response of the commercial DiCon 2×2 prism switch used in the experiment. It is noted that the upper trace of the inset represents the US signal in the working path, while the lower trace is for the US signal in the protection path after the protection switching. The lower power level observed in the protection path is because an attenuator (ATT) was inserted in the protection path to distinguish the two different paths (working and protection).

To show the network scalability of the proposed WDM-PON architecture, a power budget analysis was carried out and the results are given in Table II. In the analysis, we assume that the output power of CW light from a laser diode is about 4 dBm, the downstream EDFA (being placed after the AWG in the transceiver unit) has a gain of 20 dB and the RSOA has a saturated output power of 7.5 dBm when it is biased at 30 mA and the injected optical power is equal to or greater than

Fig. 4. (Color online) Measured BER of the 10 Gbit/s DS and 1.25 Gbit/s US signals in both the working and protection modes at 1545.5 nm. The inset shows the switching time during traffic restoration.

TABLE II
POWER MARGIN CALCULATION FOR DOWNSTREAM AND UPSTREAM DATA

Element insertion loss	Downstream	Upstream
Laser output power at OLT (dBm)	4	
EDFA amplifier gain (dB)	20	
Injected power into RSOA (dBm)		≥ -15
RSOA saturated output power (dBm)		7.5
MZM loss (dB)	5	
Circulator insertion loss (dB)	0.8	0.8
AWG insertion loss (dB)	5×2^a	5×2^a
OS insertion loss (dB)	1	1
20 km (FF + DF) SMF loss (dB)	5	5
OC insertion loss at ONU (dB)	3	3
Insertion loss (dB)	24.8	19.8
Average ^b receiver sensitivity (dBm)	-17.8	-29.5
Power margin (dB)	17	17.2

Notes.

^a “ $\times 2$ ” means the optical signal experiences the loss twice.

^b An average value is taken between the working and protection modes.

-15 dBm. The total power losses include a 5 dB insertion loss induced by the MZM, an insert loss of 0.8 dB for the optical circulator, an insert loss of 5 dB for the $1 \times N$ AWG, an insert loss of 1 dB for the OS, a 6 dB transmission loss for 20 km (FF + DF) SMF and a 3 dB loss of the 50:50 OC. Consequently, the power margin of the DS transmission is about 17 dB with the DS average receiver sensitivity of around -17.8 dBm, and the power margin for the US case is about 17.2 dB with the US average receiver sensitivity of -29.5 dBm. These higher power margins indicate the feasibility of a longer transmission distance in the proposed WDM-PON.

IV. PERFORMANCE ANALYSIS AND DISCUSSION

To show the simplicity and effectiveness of the proposed architecture, we compare the proposed scheme with those in [4,6,9,10] in terms of the number of elements and the

TABLE III

COMPARISON OF THE NUMBER OF ELEMENTS AND THE NETWORK AVAILABILITIES FOR DIFFERENT PROTECTION SCHEMES

Number of elements			Scheme in [4]	Scheme in [6]	Scheme in [9]	Scheme in [10]	Our scheme
Shared parts (including OLT, FF and RN)	OLT	Transceivers	N	$N - 1$	N	N	N
		Circulators	0	1	0	0	N
		WDM filters	N	$N + 1$	N	N	0
		$1 \times N$ AWGs	1	1	1	2 ^a	2 ^b
		OSs	1	0	1	2	1
	FFs		2	2	2	2	2
	RN	$1 \times N$ AWGs	1	2 ^a	2 ^a	2 ^a	2
		OCs	$N + 1$	0	0	0	0
ONU number			N	$N - 1$	N	N	N
Dedicated parts (including ONU, DF and IF)	ONU	Transceivers	1	1	1	1	1
		WDM filters	2	1	2	1	0
		OSs	2	1	0	0	0
		OCs	0	0	1	0	1
		DFs	1	2	1	1	2
	IFs		1/2	0	1	0	0
Wavelengths used per ONU			2	2	2	2	1
Centrally controlled APS			No	No	Yes	Yes	Yes
Protection capability			FF and DF	FF and DF	DF	FF	FF and DF
Overall network availability			99.99928%	99.99857%	99.95824%	99.99157%	99.99940%
Mean down-time (min/year)			3.77	7.53	291.47	44.31	3.17

Notes.^a A $2 \times N$ AWG or $N \times N$ AWG are functionally equivalent to a pair of $1 \times N$ AWGs.^b In our scheme, two $1 \times N$ AWGs are used in the OLT; one is in the transceiver unit and the other is in the power monitoring unit.

network availabilities as shown in Table III. In the proposed scheme, only one OS is used in the OLT, which is a significant reduction from $2N + 1$ OSs in [4] or $N - 1$ OSs in [6]. In each ONU, only one OC is required without a WDM filter. Thus, the ONU structure is much simplified, but also the device cost is greatly reduced. Meanwhile, the number of wavelengths used per ONU in our scheme is minimized among all existing schemes. This means that, with the same total number of wavelengths, our proposed WDM-PON can support the greatest number of users and hence has the least investment cost per user. However, there are still some limitations in this scheme. One limitation of the proposed scheme, as in the other schemes [4–10], is that it cannot support simultaneous multiple fiber cuts in a working path as well as a protection path, although the occurrence probability of simultaneous multiple fiber cuts is negligibly small in an access network. Besides, the protection switching for any DF failure will lead to a transient interruption to all the ONUs.

We next evaluate the overall network availability using the availability modeling methodology reported in [17,18]. The block diagrams for calculating the unavailability of different protection schemes are given in Fig. 5. Each block in the figure represents either a device/system or a fiber link. For a series connection of two or more blocks, the series connection system fails if one or more blocks fails. For a parallel connection of two or more blocks, the parallel connection system fails if and only if all of the blocks in parallel fail. We assume that all the blocks are independent of each other, and each block has a very small value of unavailability (refer to Table IV). Hence, the unavailability of a parallel connection system is

equal to the product of the unavailabilities of the blocks in parallel, while the unavailability of a series connection system is approximately equal to the sum of the unavailabilities of the blocks in series. The unavailability of a block α in Fig. 5 is denoted by U_α . The descriptions of symbols and their typical values of element unavailability are listed in Table IV [17,18]. The unavailabilities U_{FF} , U_{DF} and U_{IF} are calculated by multiplying the length of the FF, DF and interconnection fiber (IF) by the fiber unavailability of a unit length U_F . We assume that the average length of the FF is 15 km, DF 5 km and protective IF 2 km. The expressions of the connection unavailabilities for the considered protection schemes are given by the following equations:

$$U_{[4]} = (U_{TRX}^{OLT} + U_{OC} + U_{WDM} + U_{AWG} + U_{OS}) + (U_{FF1} \times U_{FF2}) + U_{OC} + U_{AWG} + U_{OC} + (U_{DF1} + U_{WDM} + U_{OS}) \times (U_{DF2} + U_{WDM} + U_{IF} + 3 \times U_{OS}) + U_{TRX}^{ONU} + U_{WDM}, \quad (2)$$

$$U_{[6]} = U_{TRX}^{OLT} + U_{WDM} + U_{AWG} + 2 \times U_{BLS} + 2 \times U_{WDM} + U_{Circulator} + U_{OC} + (U_{FF1} + U_{AWG} + U_{DF1}) \times (U_{FF2} + U_{AWG} + U_{DF2}) + U_{OS} + U_{TRX}^{ONU} + U_{WDM}, \quad (3)$$

$$U_{[9]} = (U_{TRX}^{OLT} + U_{WDM} + U_{AWG} + U_{OS}) + (U_{FF1} + U_{FF2}) + U_{AWG} + (U_{DF1} + U_{WDM}) \times (U_{DF2} + U_{IF} + U_{WDM}) + U_{OC} + U_{TRX}^{ONU} + U_{WDM}, \quad (4)$$

Fig. 5. (Color online) Block diagrams for calculating the unavailability of different protection schemes: (a) scheme in [4], (b) scheme in [6], (c) scheme in [9], (d) scheme in [10] and (e) our proposed protection scheme.

$$U_{[10]} = \left(U_{\text{TRX}}^{\text{OLT}} + U_{\text{WDM}} + U_{\text{AWG}} + U_{\text{OS}} + 2 \times U_{\text{BLS}} + U_{\text{OC}} + U_{\text{OS}} \right) + (U_{\text{FF1}} \times U_{\text{FF2}}) + U_{\text{AWG}} + U_{\text{DF}} + U_{\text{TRX}}^{\text{ONU}} + U_{\text{WDM}}, \quad (5)$$

$$U_{\text{proposed}} = \left(U_{\text{TRX}}^{\text{OLT}} + U_{\text{Circulator}} + U_{\text{AWG}} + U_{\text{OS}} \right) + (U_{\text{FF1}} + U_{\text{AWG}} + U_{\text{DF1}}) \times (U_{\text{FF2}} + U_{\text{AWG}} + U_{\text{DF2}}) + U_{\text{OC}} + U_{\text{TRX}}^{\text{ONU}}. \quad (6)$$

Our calculations are based on unavailability data in Table IV [17,18]. Hence, the connection availability A of a PON system is calculated by $A = 1 - U$, where U is the unavailability obtained from Eqs. (2)–(6). The results given in Table III show that our protection scheme achieves the highest availability, higher than 99.999% (5 nines) due to simple architecture and simultaneous protection against both FFs and DFs.

V. CONCLUSION

We have proposed and experimentally demonstrated a centrally controlled intelligent protection scheme for survivable colorless WDM-PONs. A novel logic decision unit in conjunction with a power monitoring unit is implemented in the OLT to enable intelligent protection switching in more practical operation scenarios. The proposed scheme provides 1:1 downstream protection and 1 + 1 upstream protection

TABLE IV
UNAVAILABILITY OF DIFFERENT ELEMENTS

Elements	U^a	Elements	U^a
OLT (TX and RX)	$U_{\text{TRX}}^{\text{OLT}} = 5.12 \times 10^{-7}$	WDM filter	$U_{\text{WDM}} = 3 \times 10^{-7}$
ONU (TX and RX)	$U_{\text{TRX}}^{\text{ONU}} = 1.54 \times 10^{-6}$	OC	$U_{\text{OC}} = 3 \times 10^{-7}$
AWG	$U_{\text{AWG}} = 1.2 \times 10^{-6}$	OS	$U_{\text{OS}} = 1.2 \times 10^{-6}$
Circulator	$U_{\text{Circulator}} = 3 \times 10^{-7}$	BLS ^b	$U_{\text{BLS}} = 4 \times 10^{-6}$
Fiber (/km)	$U_F = 1.37 \times 10^{-5}$ (/km)		

Notes.

^a U , unavailability.

^b BLS, broadband light source.

capabilities. The scheme can deal with practical protection switching scenarios by monitoring the optical power of each channel on both the working and protection paths and performing intelligent logic decisions, which have not been considered previously. In addition, the power monitoring unit in the OLT can record these detection results on the connection status of each fiber path in each channel, thus facilitating an effective protection switching and a faster failure recovery. The scheme feasibility has been experimentally verified with 10 Gb/s downstream and 1.25 Gb/s upstream transmissions. The proposed architecture not only simplifies the ONU design, but also significantly reduces network complexity in terms of number of network elements while offering the improved wavelength resource utilization and the highest network availability as compared with all other existing schemes.

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