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Discussion

A CLS-based survivable and energy-saving WDM-PON architecture

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ABSTRACT

We propose and demonstrate an improved survivable and energy-saving WDM-PON with colorless ONUs. It incorporates both energy-saving and self-healing operations. A simple effective energy-saving scheme is proposed by including an energy-saving control unit in the OLT and a control unit at each ONU. The energy-saving scheme realizes both dozing and sleep (offline) modes, which greatly improves the energy-saving efficiency for WDM-PONs. An intelligent protection switching scheme is designed in the OLT, which can distinguish if an ONU is in dozing/sleep (offline) state or a fiber is faulty. Moreover, by monitoring the optical power of each channel on both working and protection paths, the OLT can know the connection status of every fiber path, thus facilitating an effective protection switching and a faster failure recovery. The improved WDM-PON architecture not only significantly reduces energy consumption, but also performs self-healing operation in practical operation scenarios. The scheme feasibility is experimentally verified with 10 Gbit/s downstream and 1.25 Gbit/s upstream transmissions. We also examine the energy-saving efficiency of our proposed energy-saving scheme by simulation, which reveals that energy saving mainly arises from the dozing mode, not from the sleep mode when the ONU is in the online state.

1. Introduction

With the emergence of bandwidth-intensive applications such as high-definition Internet protocol television (HD-IPTV), video on demand (VoD) and video-conferencing, a wavelength division multiplexed passive optical network (WDM-PON) has been considered to be the most suitable technology of the next-generation broadband access networks [1,2]. In particular, a WDM-PON with centralized light sources (CLS) located at the central office (CO) is highly recognized as a cost-effective and flexible solution to deliver gigabit broadband services to subscribers, since it realizes source-free colorless optical network units (ONUs) at user-side and has a better wavelength utilization efficiency [3,4]. Several CLS-based WDM-PONs have been reported, including wavelength reuse schemes [5,6] and wavelength seeding schemes [7–10]. Among them, the wavelength seeding technique using reflective semiconductor optical amplifiers (RSOAs) with on–off keying (OOK) at ONUs appears to have a great potential for practical deployments, because it can provide an optical gain to the re-modulated signal and suppress the interference from the downstream signal to the upstream signal when operating at the gain-saturation region [9,10].

However, WDM-PONs employing CLS in the optical line terminal (OLT) have a critical energy consumption issue. In such a WDM-PON, even if there is no downstream data to be sent to an ONU which yet has upstream data to be sent to the OLT, the corresponding transmitter in the OLT has to continuously transmit the downstream light at the normal optical power, since ONU does not employ any light source and it cannot send its upstream signal without the downstream carrier. In practice, an ONU may be offline (i.e., shutdown) for certain periods in a day (e.g., in the early morning or at night). Even during online period of an ONU, when there is neither downstream nor upstream data on a certain wavelength channel, it is natural for the ONU and its associated transceiver in the OLT to stop their signal transmission and enter into an energy-saving mode, in order to reduce energy consumption. Recently, several energy-saving schemes considering “sleep mode” for WDM-PONs were proposed [11–13]. The work in [11] used an additional tuneable laser in the OLT to poll those ONUs in sleep mode in a time division multiplexing (TDM) way. Upon receiving the polling light, those sleeping ONUs with data to be sent modulate the polling light with a “recovery request” signal. The authors of [12] used an additional broadband light-emitting-diode (LED) which is spectrally sliced by an arrayed waveguide grating (AWG). Each spectrally-sliced light acts as a supervisory

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carrier for an ONU. Those sleeping ONUs with data to be sent modulate the received supervisory carrier with a radio frequency (RF) signal, which acts as a "recovery request". In [13], the amplified spontaneous emission (ASE) spectrum from an RSOA at each ONU was modulated by a pilot RF signal and sent to the OLT to resume data transmission from the "sleep mode". However, all these existing schemes require that each sleeping ONU with data to be sent modulates a "recovery request" signal to either the supervisory light coming from the OLT [11,12] or the ASE light generated by an RSOA in the ONU [13], which increases the system complexity. Moreover, these existing schemes only considered one energy-saving mode (i.e., sleep mode), and hence their energy-saving efficiency is very low (refer to Section 4 for details). Recently, we have reported an effective energy-saving scheme that incorporates both dozing and sleep modes in the ONUs [14]. However, only the dozing mode is implemented in the transceivers of the OLT, since the receivers in the OLT need to be always "ON" to monitor the upstream ASE light power. In this paper, both dozing and sleep modes are simultaneously implemented in each ONU and its associated transceiver of the OLT.

Besides the energy-saving issue in a WDM-PON, monitoring and protection against fiber failures are also imperative for network operators to enhance the access network reliability. With the rapid increase of WDM-PON transmission capacity, any possible failure of either feeder fibers (FFs) or distribution fibers (DFs) will disrupt the services, leading to a large amount of data loss. To date, several protection schemes for WDM-PONs have been reported [15–21]. The distributed control schemes [15–17] require optical switches (OS) and monitoring units installed at each ONU to perform the protection switching operation, which increases the complexity and cost of ONUs. Although some centrally controlled protection schemes [18,19] have also been proposed, they require either N OSs [18] or N electrical switches [19] in the OLT, which still has not reduced the system complexity and cost. Compared with the schemes in [18,19], the protection schemes in [20,21] require only one OS located in the OLT, but only the DF [20] or the FF [21] is protected from fiber failure and thus the network availability is relatively low.

Moreover, all the above protection schemes [15–21] are based on simple power monitoring and hence they only work under the assumption that all the transmitters in the ONUs and the OLT continuously transmit optical signals. However, in practice, (i) some transceivers of ONUs or the OLT may frequently enter into sleep mode whenever there is no data to be sent in order to save energy consumption [11–13], (ii) some ONUs may be shut down whenever users are offline, and (iii) fiber faults happen to occur during the time when ONUs are offline or when ONUs are in sleep mode. In the above three cases, none of the above protection schemes [15–21] based on simple power monitoring can work. Specifically, for case (i) (or case (ii)) when an ONU is in sleep mode (or is offline), since no optical signal is received from that ONU, the corresponding power monitor in the OLT would assume 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), for instant, if a fiber failure happens to occur in the protection path of an ONU (e.g., the protection DF fails) during the time when that ONU is in sleep mode (or is offline), 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. We have recently reported an intelligent protection scheme in a WDM-PON [22].

In this paper, to deal with all the above energy-saving and protection problems associated with CLS-based WDM-PONs, we propose an improved CLS-based WDM-PON architecture, which incorporates both the energy-saving and self-healing operations. An improved energy-saving scheme implementing both dozing and sleep modes in both the ONUs and the OLT greatly improves the energy-saving efficiency for WDM-PONs. Meanwhile, a power monitoring unit and a protection switching control unit are built into the OLT, whereby the optical powers on both the working and protection paths are monitored simultaneously. Thus, the centrally controlled protection scheme can tell the connection status of both the working and protection paths of each channel, and hence can perform an intelligent protection switching with the aid of the logic decision, which is made at the protection switching control unit. (Note that, with the existing schemes, the optical power of the working path only is monitored and no logic decision is provided.) Moreover, the detection results recorded by the power monitoring unit facilitate a faster failure recovery. Since energy-saving and protection-switching are incorporated in the proposed CSL-based WDM-PON, the interaction between them (i.e., synchronization issue of logic signals both in working and protection paths) are discussed (refer to Section 2.4 for details). The proposed CLS-based WDM-PON architecture can not only significantly reduce energy consumption, but can also deal with self-healing operation in various practical operation scenarios. The scheme feasibility is verified experimentally with 10 Gbit/s downstream and 1.25 Gbit/s upstream transmission over a 20 km fiber transmission. The energy-saving efficiency is evaluated by simulation, which reveals that energy saving mainly arises from the dozing mode, not from the sleep mode when the ONU is in the online state.

The rest of the paper is organized as follows. Section 2 describes the proposed energy-saving and protection switching scheme in detail. Section 3 experimentally demonstrates the feasibility of the proposed WDM-PON architecture. Section 4 evaluates the energy-saving efficiency of the proposed scheme in comparison with the existing schemes. Section 5 concludes this paper.

2. Proposed architecture and operation principle

In this section, we first introduce the overall architecture of the proposed CLS-based WDM-PON. Then the improved energy-saving and protection switching schemes for WDM-PONs are described separately. At last, the synchronization issue of logic signals in the protection switching control unit is discussed.

2.1. Proposed CLS-based WDM-PON architecture

Fig. 1 shows the proposed energy-saving and centrally-controlled self-healing CLS-based WDM-PON architecture with N colorless ONUs. The OLT located at the CO has two functional units (i.e., transceiver unit and power monitoring unit) and two logic decision units: energy-saving control unit and protection switching control unit. All the input and output signals of both logic decision units are represented by logics "0" and "1". As shown in Fig. 1, the transceiver unit includes N transceivers, supporting N ONUs. In each transceiver, a transmitter (TX) generates a downstream (DS) signal and an optical circulator is used to separate DS and upstream (US) signals. Apart from receiving the US signal, an US receiver (RX) also acts a monitor for monitoring the US power in the working path in the normal mode. Given the power detection result, the US RX generates corresponding electrical logic signals, which are split and then fed to both the logic decision units. The wavelengths of all channels are multiplexed by a $1 \times N$ AWG in the transceiver unit. The multiplexed signal is fed to port 1 of a 2×2 OS in the OLT via a coarse wavelength division multiplexer (CWDM). The purpose of the inserted CWDM will be explained in Section 2.2. Port 3 of the OS is connected to another AWG with the same free spectral range (FSR) via an optical coupler (OC) and an erbium-doped

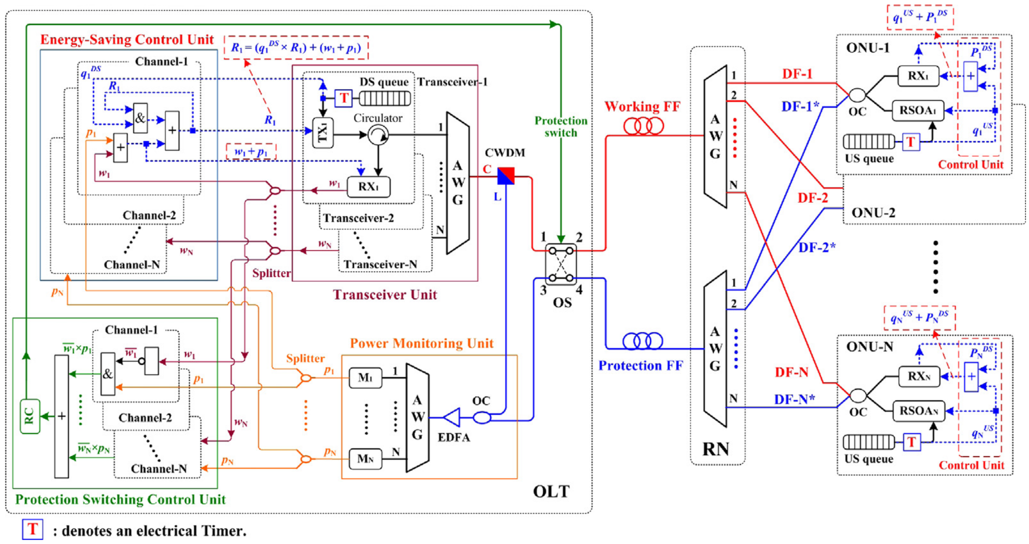

Fig. 1. Schematic diagram of the CLS-based WDM-PON architecture with the proposed energy-saving and centrally-controlled self-healing scheme.

Table 1
Operation modes for each ONU and its associated transceiver in the OLT according to DS and US transmission states.

Upstream (US) data	Downstream (DS) data	ONU operation mode	OLT operation mode
Existing	Existing	**Active (RSOA[a] and RX ON)**	**Active (TX and RX ON)**
Existing	No existing	**Active (RSOA and RX ON)**	**Active (TX and RX ON)**
No existing	Existing	**Dozing (RSOA OFF, RX ON)**	**Dozing (TX ON, RX OFF)**
No existing	No existing	**Sleep (RSOA and RX OFF)**	**Sleep (TX and RX OFF)**

[a] RSOA is the TX of ONU.

fiber amplifier (EDFA) in the power monitoring unit. The power monitoring unit consists of N power monitors for monitoring the power of respective US signals on the protection path in the normal mode, and generating respective electrical logic signals, which are also split and then fed to both the logic decision units. It is worth to mention that only one OS is used in the OLT, which is a significant reduction from 2N+1 OS's in [15] or $N-1$ OS's in [17].

Ports 2 and 4 of the OS are connected to the two $1\times N$ AWGs with the same FSR at the remote node (RN), via two separate FFs (working and protection FFs). After being de-multiplexed by two AWGs at the RN, each DS 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 OC is used to combine two DFs and to split the DS signal power into two parts: one part is fed to a DS RX for DS data detection; the other is amplified and re-modulated with US data via a RSOA operating in its gain-saturated region, and then sent back to the OLT.

2.2. Efficient energy-saving scheme

As shown in Fig. 1, the energy-saving control unit in the OLT has N identical logic modules, each of which is related to a wavelength channel. From the viewpoint of the RX and TX behavior, three operation modes, namely active, sleep and dozing modes, are defined for each ONU and its associated transceiver in the OLT (refer to Table 1). In the active mode, both the RX and TX are turned "ON" and hence the ONU and its associated transceiver in the OLT consume the full power P_A. In the sleep mode, both the RX and TX are "OFF", while maintaining an ability to wake up with a local stimulus. For example, an US transmission request from local user can trigger the wakeup of that sleeping ONU. This mode can be applied when there is neither DS nor US traffic simultaneously (the corresponding ONU is in the online state). Hence, the sleep mode consumes the lowest power P_S, leading to the maximum energy saving. It is noted that the sleep mode can also be applied to the case when the ONU is shut down (i.e., offline state). The dozing mode defined for an ONU is different from that for its associated transceiver in the OLT. When an ONU is in dozing mode, its TX (i.e., RSOA) is turned off, but its RX is still "ON" and hence it can continue to receive DS signal. When a transceiver in the OLT is in dozing mode, its TX is "ON" and hence it can continue to transmit DS data, while its RX is turned off. The dozing mode is very suitable for many common application scenarios where the DS traffic volume is extremely large while there is no US traffic temporarily, for example, video on demand (VoD) and massive file download. Due to the partial shutdown of a transceiver in the ONUs and the OLT, the power usage in the dozing mode is reduced to a modest level P_D ($P_S < P_D < P_A$).

Since a WDM-PON essentially provides a point-to-point wavelength connection between each ONU and its associated transceiver in the OLT. Hence in what follows, we focus on the operation of a pair of an ONU and its associated transceiver in the OLT, specifically ONU-1 and Transceiver-1 in the OLT, as any of the other pairs is the same.

As long as US transmission of ONU-1 exists, the signal q_1^{US} in ONU-1 is logic "1", which keeps the US TX_1 (i.e. $RSOA_1$) to stay in the "ON" state and sends US signal carrier. In the normal mode, the US power is detected in the OLT by either the US RX_1 through the working path, or the power monitor M_1 through the protection path, or both of them. Thus a logic signal "$w_1+p_1=1$" is generated and thus the output signal R_1 is set to be logic "1", which ensures both DS TX_1 and US RX_1 in the OLT stays in the "ON" state too. When the DS RX_1 in ONU-1 detects the DS carrier power, the signal P_1^{DS} is set to be logic "1", which further guarantees that DS RX_1 stays in "ON" state. Hence in the above case, both ONU-1 and Transceiver-1 in the OLT are in the active mode (refer to first two rows of Table 1).

Referring to Fig. 2, whenever the control unit in ONU-1 finds that there has been no US data in the US data queue for a certain period of threshold time T_{th}, which is counted by an electrical timer (denoted as "T" in Fig. 1), a logic "$q_1^{US}=0$" is generated by the US data queue to turn off the $RSOA_1$ and triggers ONU-1 from the active to the dozing mode. Since $RSOA_1$ in ONU-1 is turned off, both the US RX_1 and the power monitor M_1 in the OLT immediately detect a drastic US power loss. Thus a logic signal "$w_1+p_1=0$" is generated to turn off the US RX_1, and hence the Transceiver-1 is also switched from the active mode to dozing mode (refer to the 3rd row of Table 1 and No. 1 state transition in Fig. 2). So the logic expression of control signal for the US RX_1 in the OLT is "w_1+p_1" (refer to Fig. 1).

Under the scenario where both ONU-1 and Transceiver-1 in the OLT are in dozing mode, there are two possible state transition cases. Let us consider the first case (refer to the sequence (a) in Fig. 2): when both ONU-1 and Transceiver-1 in the OLT are in dozing mode, once there is US data arriving in the US data queue of the dozing ONU-1, a resuming signal "$q_1^{US}=1$" is first generated to activate $RSOA_1$ in ONU-1. As there still exists DS carrier in C-band (Transceiver-1 in the OLT is in the dozing mode), $RSOA_1$ is wavelength-seeded and thus its US light sent to the OLT is also in C-band. Upon the US light power being detected by the power monitor M_1 in the OLT, the logic "p_1" becomes "1" (thus $w_1+p_1=1$), which turns on US RX_1 and activates Transceiver-1 in the OLT (refer to No. 2 state transition in Fig. 2).

Next let us consider the second case (refer to the sequence (b) in Fig. 2): when both ONU-1 and Transceiver-1 in the OLT are in dozing mode, once there exists no DS data in the DS data queue for a time period of T_{th}, (which is counted by an electrical timer "T",) the DS TX_1 is also turned off by a logic signal "$q_1^{DS}=0$". As a result Transceiver-1 in the OLT enters into the sleep mode. Due to the absence of the DS carrier, the DS RX_1 in ONU-1 detects a drastic DS power loss and thus produces a logic signal "$P_1^{DS}=0$", which switches ONU-1 into the sleep mode (refer to No. 3 state transition in Fig. 2 and the 4th row of Table 1). Here the control signal designed for the DS RX_1 in ONU-1 is "$q_1^{US}+P_1^{DS}$" (refer to Fig. 1). It can be seen that the precondition of turning off the DS RX_1 in ONU-1 is "$q_1^{US}=0$", which indicates that the US TX_1 (i.e., $RSOA_1$) has already been turned off.

We can conclude that the first state transition case will take place under the condition that the US resuming request "$q_1^{US}=1$" is prior to the timeout signal "$q_1^{DS}=0$"; otherwise, the second state transition case will occur first.

It is important to note that the state transition from the sleep mode to the dozing mode in Fig. 2 (i.e., the inverse process of No. 3 state transition) is prohibited and unnecessary. As we know, the "client-server model" is generally adopted in a PON. Without the dada request from the sleeping ONU-1 (client), the OLT (server) could not send any DS data to a sleeping ONU-1 and hence the DS transmission would not take place. The sleeping ONU-1 can be waked up only by its US data transmission request "$q_1^{US}=1$". For this reason, the control signal R_1 for DS TX_1 in Transceiver-1 in the OLT is fed back to the input side. Thus R_1 is expressed as

$$R_1=(R_1q_1^{DS})+(w_1+p_1) \tag{1}$$

From Eq. (1), we know that when the signal R_1 is logic "0" (i.e. the Transceiver-1 in the OLT is in the sleep mode), the R_1 will not be changed to logic "1" by the signal q_1^{DS}; it can be changed to logic "1" if and only if there is the US light received in the OLT (i.e., w_1 or p_1 or both of them are logic "1"). It can be also known from Eq. (1) that the precondition of turning off the DS TX_1 in the Transceiver-1 is that the US transmission has already been halted (i.e., "$w_1+p_1=0$"), which satisfies with the requirements of a CLS-based WDM-PON. Therefore, in the improved energy-saving scheme, the active mode could not be directly changed into the sleep mode and it must go through the dozing mode first. For the

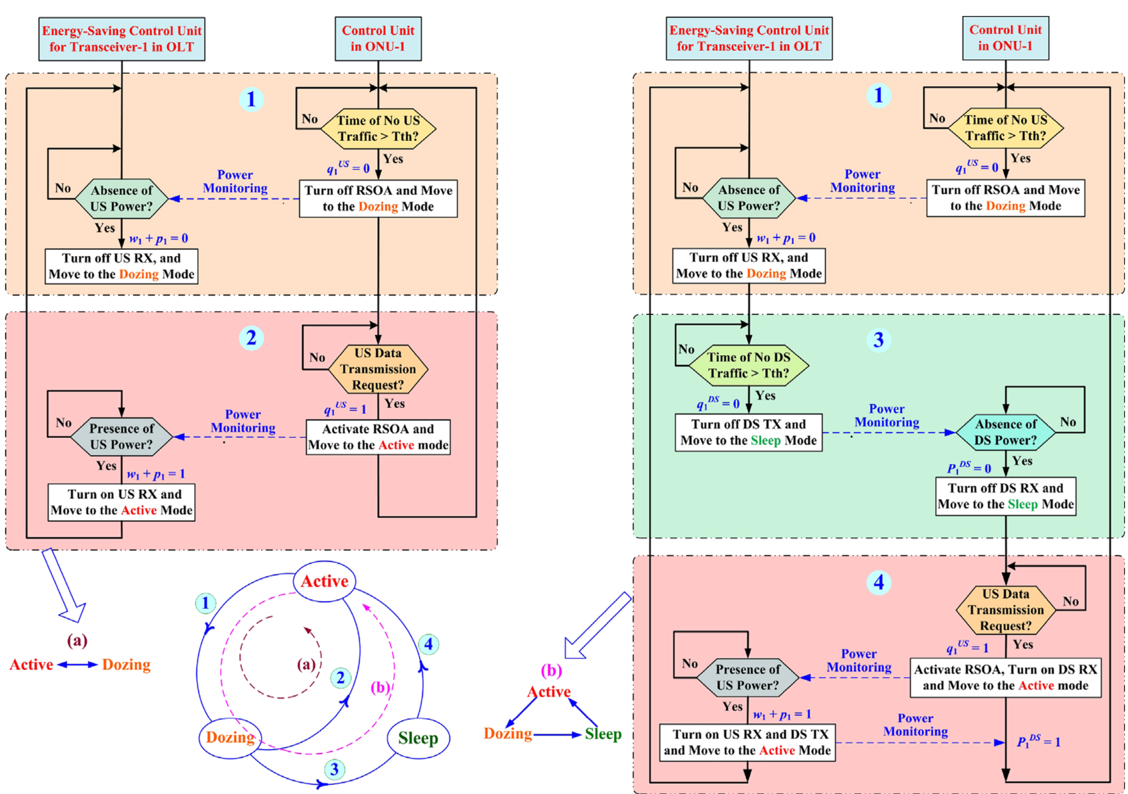

Fig. 2. The two possible sequences (a) and (b) of state transitions for ONU-1 and Transceiver-1 in the OLT in our proposed energy-saving scheme.

clarity of presentation, a list of control signals designed for each ONU and its associated transceiver in the OLT is given in Table 2.

When both ONU-1 and Transceiver-1 in the OLT are in sleep mode, once there is US data arriving in the US data queue in the sleeping ONU-1, a resuming signal "$q_1^{US}=1$" is generated immediately to activate the $RSOA_1$ in ONU-1. As there is no DS signal, the $RSOA_1$ is not wavelength-seeded and its broadband ASE light is sent to the OLT through both the working and protection paths. After being spectrum-sliced by the AWGs at the RN, the ASE light at wavelengths (λ_1+$mFSR$, $m=\pm1, \pm2,\ldots$) is transmitted to the OLT, due to the cyclic spectral property of the AWG. It is noted that we insert a CWDM to filter out the L-band components of the spectrum-sliced ASE light, which is transmitted on the working path in the normal mode. Then the filtered L-band components is combined with the other spectrum-sliced ASE light transmitted on the protection path via an OC in the power monitoring unit. After being amplified by an EDFA and de-multiplexed by an AWG, the combined US ASE light power is detected by the power monitor M_1 ($p_1=1$). Thus the "w_1+p_1" becomes "1" to activate Transceiver-1 in the OLT, which results in transmitting the DS light in the continuous wave (CW) to ONU-1 (refer to No. 4 state transition in Fig. 2). After receiving the DS carrier in C-band, ONU-1 resumes the normal US data transmission and DS signal receiving.

The purpose of the CWDM can be explained as follows. Suppose that the CWDM is not used. In such a case, if a DF on the protection path, say DF-1*, fails just during the period when the ONU-1 is in the dozing or the sleep mode (or offline), both the power monitor M_1 and the US RX_1 in the OLT will not be able to detect any US light power even when ONU-1 wakes up (or is turned on). This is because during the dozing or the sleep mode, the US RX_1 in the OLT is already turned off and hence cannot detect any US power through the working path. As a result, the OLT will completely lose the connection with the ONU-1 unless the DF-1* failure is repaired by a person. If the CWDM is used, as shown in Fig. 1, the L-band component of the US ASE power transmitting through the working path can also be detected by the power monitor M_1 in the above-stated case. Upon detecting the US ASE power, the associated Transceiver-1 in the OLT can be activated.

2.3. Intelligent protection switching scheme

In our proposed WDM-PON architecture, an intelligent protection switching scheme is also incorporated as shown in Fig. 1. The novel protection switching control unit in the OLT consists of N identical logic modules, each of which is related to a channel, and a multi-input-single-output logic OR gate. Here we still take an example of ONU-1 and Transceiver-1 in the OLT for the scheme description.

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 US RX_1 and the power monitor M_1 simultaneously experience a drastic power loss, it is assumed that ONU-1 either enters into sleep/dozing mode or is shut down (i.e., offline). In such a case, no protection switching will take place. Actually, the proposed protection scheme can also protect against simultaneous multiple-link failures, except for a rare case where the two DFs (i.e., DF-1 and DF-1*) of ONU-1 or the two FFs break down simultaneously. Table 3 provides the logic decision results of the protection switching control unit based on the logic inputs on both the working and protection paths of each channel.

In the normal working mode, the 2×2 OS in the OLT is set to the bar state (i.e., 1–2 and 3–4 connections). Thus, the DS signal is delivered only on the working path, consisting of the working FF and DF-1 (red path). Since a 2×2 OC is used in each ONU, the US signal is split into two copies, one of which transmitted in the working path is sent to the Transceiver-1 in the OLT; the other in the protection path is fed into the power monitor M_1.

In the case of any working DF failure (e.g., DF-1), the US RX_1 in Transceiver-1 will detect the loss of that US signal, and hence a logic signal "$w_1=0$" will be generated. But, in this case, the M_1 in the power monitoring unit can still detect light power, and a signal "$p_1=1$" will be generated. Consequently, the output of the protection switching control unit will be logic "1", which triggers the 2×2 OS to the cross state (i.e., 1–4 and 3–2 connections) to setup 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, according to the detection results of the N power monitors, the power monitoring unit can tell if it is a DF or the 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 US RX_1 detects the presence of light ($w_1=1$) while the M_1 detects no light ($p_1=0$), it indicates that the protection DF-1* fails, but in this case no protection switching will take place.

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

$$[(\overline{w_1}p_1)+(\overline{w_2}p_2)+\ldots+(\overline{w_N}p_N)] \tag{2}$$

The proposed self-healing WDM-PON can provide centrally-controlled protection capability against the failures of both FFs and DFs.

The proposed protection scheme is capable of discriminating a real fiber failure from three special cases in practical operation as mentioned in Section 1. Specifically, in the case (i) where the ONU is set to sleep/dozing mode or the case (ii) where the ONU is shut down (i.e., offline), the protection scheme can effectively avoid malfunction of the 2×2 OS.

Table 2
List of control signals for each ONU and its associated transceiver in the OLT.

ONU-*i* (*i*=1, 2,…, *N*)	
US TX$_i$ (RSOA$_i$)	q_i^{US}
DS RX$_i$	$q_i^{US}+P_i^{DS}$
Transceiver-*i* in OLT (*i*=1, 2,…, *N*)	
DS TX$_i$	$R_i=(R_iq_i^{DS})+(w_i+p_i)$
US RX$_i$	w_i+p_i

Table 3
Truth table for the detection states of the US light on both working and protection paths of each channel.

Detection state of the US RX_i in the working path	Detection state of the power monitor M_i in the protection path	Output of the logic module for channel-i ($i=1, 2,\ldots, N$)
$w_i=1$ (with light)	$p_i=1$ (with light)	0 (normal working mode)
$w_i=0$ (no light)	$p_i=1$ (with light)	1 (do protection switching)
$w_i=1$ (with light)	$p_i=0$ (no light)	0 (no switching, but to repair protection fiber)
$w_i=0$ (no light)	$p_i=0$ (no light)	0 (ONU is in dozing/sleep mode or shut down)

In the case (iii), even if a fiber failure happens to occur in the protection path during the time when that ONU is in sleep mode (or is offline), the power monitor M_1 can always detect the US spectrum-sliced ASE light power. It is because that the L-band components of the US spectrum- sliced ASE light transmitted on the working path are also forwarded to the power monitoring unit via a CWDM in the OLT. Thus, the logic signal p_1 becomes "1" and the "$w_1 + p_1 = 1$" is generated, which switches Transceiver-1 in the OLT to its active mode.

2.4. Logic signal synchronization issue for the protection switching control unit

As stated above, the US signal of any wavelength channel is always received by the corresponding transceiver in the OLT, while the corresponding monitor in the power monitoring unit only needs to detect the power of the US signal. Hence, there is no synchronization issue in receiving the US signal of each channel.

However, the synchronization issue of the logic signals w_i and p_i generated by the US RX_i and the associated monitor M_i of the corresponding channel in the OLT cannot be ignored in some special situations. For example, (a) when ONU-i turns off its US TX_i (i.e., $RSOA_i$) to enter into the dozing mode from the active mode, or (b) when ONU-i activates its US TX_i (i.e., $RSOA_i$) from the dozing/sleep mode (or offline state), both the US RX_i and the power monitor M_i of the corresponding channel may detect the power loss or rise in different times, respectively. Hence, the logic values of the signals w_i and p_i may change in different times, which may bring about a synchronization issue of the logic signals for protection switching control unit.

More specifically, 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 will lead to the light propagation time difference between the working and protection paths. 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 US RX_i can detect the power loss (or rise) by δ=0.1 ms (=20 km/(2 × 10^5 km/s)) earlier than the power monitor M_i. For example, in the aforementioned case (a), the signal w_i from the US RX_i becomes "0" by 0.1 ms earlier than the p_i from the power monitor M_i. As a result, a logic "1" will be generated by the protection switching control unit within the time difference δ=0.1 ms.

For the aforementioned case (b), our proposed energy-saving scheme would also result in the same problem that both logic signals w_i and p_i may change their values in different times. For instance, when ONU-i activates its DS RX_i and US TX_i (i.e., $RSOA_i$) from the sleep mode (or offline state), the power monitor M_i can detect the combined US ASE light power from both the working and protection paths, while the US RX_i is still in the sleep mode. Thus only p_i becomes "1", which activates the US RX_i and DS TX_i in the OLT. Just at this moment, the signal w_i still remains "0", because the C-band component of US ASE light is not wavelength-seeded and its power may be too weak to be detected by the US RX_i. Then the DS carrier in the CW from the DS TX_i reaches ONU-i and the $RSOA_i$ in ONU-i is wavelength-seeded in the C-band to resume the normal US data transmission which is sent to the OLT. After the round trip time (about 0.2 ms=(20 km × 2)/(2 × 10^5 km/s)), the w_i becomes logic "1". Hence, the w_i becomes "1" by 0.2 ms later than the p_i, which also causes the synchronization issue.

In the above two cases, the time difference δ between the logic signals w_i and p_i is very small and less than δ_{max} of 0.5 ms. In a practical system, the switching speed of the commercial opto-mechanical switch (e.g., DiCon prism used in our experiment) or thermo-optical switch is about several milliseconds [23], which is much larger than the δ_{max} of 0.5 ms. Such OS would not change its switching state within 0.5 ms and hence would not result in false protection switching. Thus, we can conclude that if the switching time of the OS used in the proposed WDM-PON is much larger than the δ_{max} of 0.5 ms, the synchronization of the logic signals can be ignored. However, if the switching time of the OS is comparable to (or smaller than) the δ_{max} of 0.5 ms, the logic signal synchronization issue is required to be dealt with carefully. In such a case, a simple solution is to insert a RC integrating circuit [24] (denoted as "RC" in Fig. 1) with a time constant of two to three times of δ_{max} between the output of the protection switching control unit and the 2 × 2 OS. In a practical optical access network, a failure recovery time of a few milliseconds can meet the requirement of current optical network standards and ultrafast switching is not a necessity. The use of OSs with a relatively low switching speed of a few milliseconds is the preferred choice, since this can not only reduce the cost, but also eliminate the need for the logic signal synchronization.

3. Experimental setup and results

The transmission performance and the protection switching time of the proposed WDM-PON were experimentally studied, using the setup shown in Fig. 3. Two ONUs (i.e., ONU-1 and ONU-2) and their associated transceivers in the OLT were implemented to demonstrate the operation principle. In the OLT, two CW lights from two laser diodes (LDs) at 1545.5 nm and 1553.6 nm were modulated via respective Mach–Zehnder modulators (MZMs), which were biased at the transmission null point and driven by a 10 Gbit/s data with a pseudo-random bit sequence (PRBS) with length of 2^{31}–1 to generate DS non-return-to-zero (NRZ) OOK signals. After being combined by a 1 × 16 AWG, the combined DS signals passed through an EDFA, an optical circulator and a CWDM before they were fed to a 2 × 2 OS. The EDFA was used to compensate the DS power loss and to improve the power budget. The 2 × 2 OS used in our experiment was a commercial DiCon prism switch, which has a switching speed of a few milliseconds, an insertion loss of 1 dB and a crosstalk of −70 dB. Two other 1 × 16 AWGs located in the RN have a channel spacing of 100 GHz and a FSR of 31 nm. The FF and DF are single mode fibers (SMFs) with lengths of 15 km and 5 km, respectively. At each ONU, one part of the DS signal was detected by an avalanche photodiode (APD) receiver; the other was amplified and re-modulated with 1.25 Gbit/s 2^{31}–1 PRBS US data via a gain-saturated RSOA. The un-cooled RSOA was biased at 30 mÅ via a Bias-T circuit and the optical power injected into the RSOA was −15 dBm. At these conditions, the RSOA was saturated with an output power of 7.5 dBm (i.e., optical gain=22.5 dB), and its 3 dB modulation bandwidth was measured to be 1.5 GHz.

We first investigated the effect of the DS extinction ratio (ER) on the bit-error-rate (BER) performances for both DS and US transmissions over 20 km (FF+DF) SMF. We here just show the experimental results for ONU-1 at 1545.5 nm. Similar results were observed for ONU-2 at 1553.6 nm. The power injected into the $RSOA_1$ in ONU-1 was maintained at −15 dBm so that the $RSOA_1$ was operated in its saturation region. The ER for all US signals was about 10 dB. We were able to achieve the error-free US transmission with the DS ER of up to 5 dB. An error floor at ~7.5 × 10^{-7} was observed for the US transmission when the DS ER was set to be 5.6. Fig. 4 shows the BER of the DS and US signals at 1545.5 nm for different DS ERs. As shown in Fig. 4, when the DS ER was increased from 3 dB to 5 dB, the BER of the DS signal was improved, while the BER of the US signal was degraded due to the higher interference from the DS signal. The insets of Fig. 4 are the eye patterns of the DS and US signals when the DS ER was 5 dB.

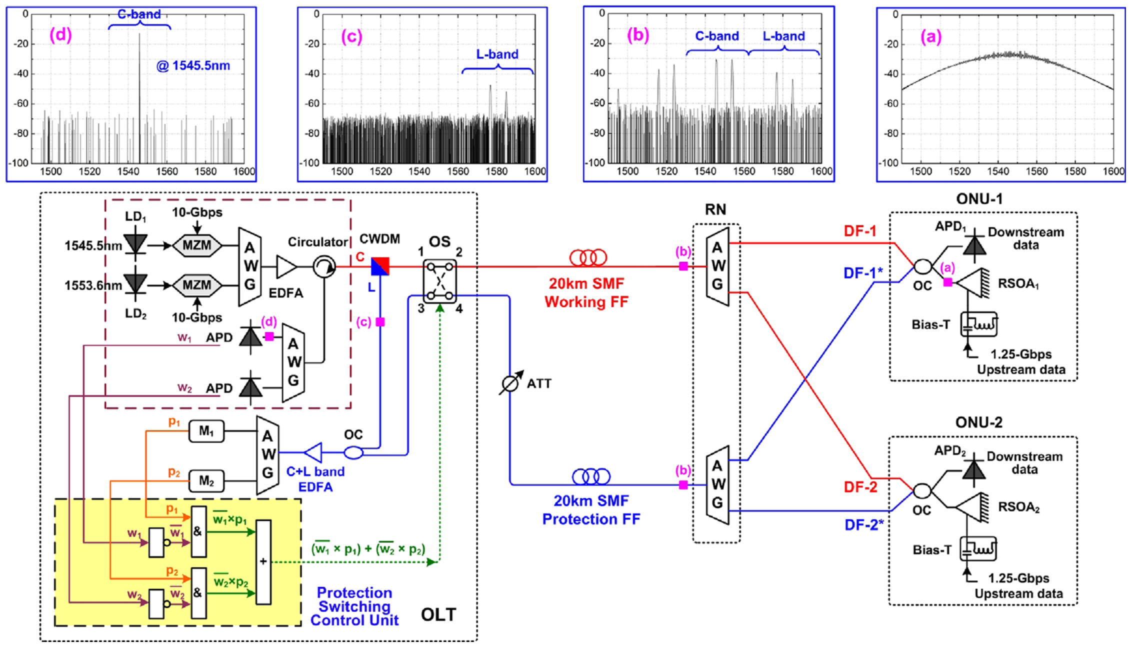

Fig. 3. Experimental setup for the centrally-controlled self-healing operation in the proposed WDM-PON architecture.

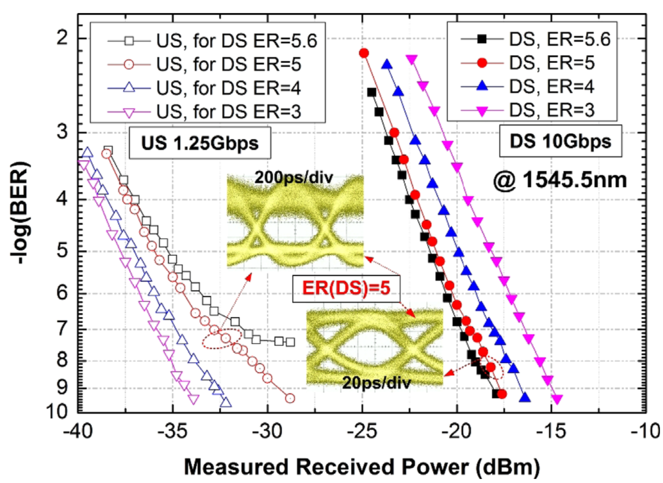

Fig. 4. Measured BER of the DS and US signals at 1545.5 nm for different DS ERs. Insets show the optical eye patterns when the DS ER is 5 dB.

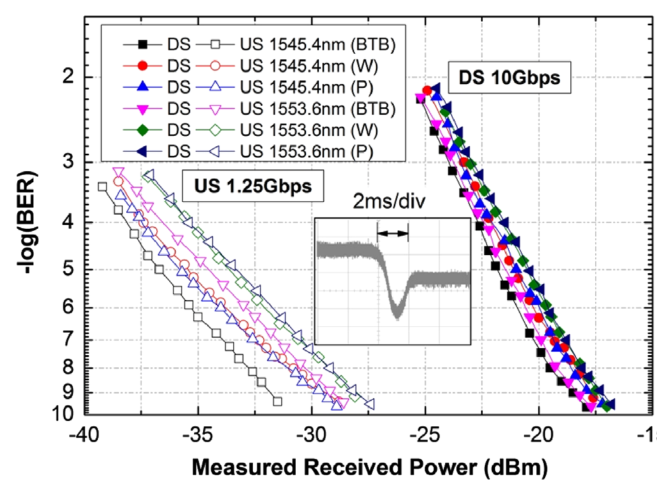

Fig. 5. Measured BER of the 10 Gbit/s DS and 1.25 Gbit/s US signals both in the working and protection modes at 1545.5 nm and 1553.6 nm. Inset shows the switching time during traffic restoration.

Fig. 5 shows the BERs for DS and US signals at 1545.5 nm and 1553.6 nm when the DS ER was 5 dB. Since the working and protection paths experience the same fiber link length and optical elements, the BER performances are similar for both paths. The receiver sensitivities of the DS signal were about −17.8 dBm at 1545.5 nm and −17.5 dBm at 1553.6 nm, respectively. In the US case the measured receiver sensitivities were about −29.5 dBm at 1545.5 nm and −28.3 dBm at 1553.6 nm, respectively. To investigate the power penalties, the BERs of the back-to-back (BTB) case are also shown in Fig. 5. For the DS transmission in both working and protection paths, the power penalties between the BTB and the 20 km SMF transmission cases were about 0.7 dB for both wavelength channels. The power penalties of US transmission in both working and protection paths were about 2.3 dB at 1545.5 nm and 1.0 dB at 1553.6 nm, respectively. The power penalty for the DS transmission is mainly due to the chromatic dispersion, as the DS data rate is 10 Gb/s, while the power penalty for the US transmission is attributed to the backscattering noise, since the US reuses the DS wavelength.

Using the experimental setup shown in Fig. 3, the fiber link (DF-1) between the AWG and the ONU-1 was intentionally disconnected to simulate the fiber cut scenario. The protection switching time was measured to be 2 ms (see inset in Fig. 5), 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 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 4. In the analysis, we assume that the output power of CW light at 1545.5 nm from a laser diode is about 4 dBm, the EDFA has a gain of 15 dB and the RSOA has a saturated output power of 7.5 dBm when it is biased at 30 mÅ and the injected optical power is equal to or greater than −15 dBm.

Table 4
Power margin calculation for DS and US signals.

Element insertion loss	DS signal	US signal
Laser output power at OLT (dBm)	4	
EDFA amplifier gain (dB)	15	
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
CWDM insertion loss (dB)	0.8	0.8
20 km (FF+DF) SMF loss (dB)	5	5
OC insertion loss at ONU (dB)	3	3
Insertion loss (dB)	25.6	20.6
Receiver sensitivity (dBm)	−17.8	−29.5
Power margin (dB)	11.2	16.4

[a] "× 2" means the optical signal experiences the loss twice.

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 × 16 AWG, an insert loss of 1 dB for the OS, a loss of 0.8 dB for the CWDM, a 5 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 11.2 dB with the DS receiver sensitivity of around −17.8 dBm, and the power margin for the US case is about 16.4 dB with the US receiver sensitivity of −29.5 dBm. These higher power margins indicate the feasibility of a longer transmission distance in the proposed WDM-PON.

To demonstrate the feasibility of the proposed energy-saving scheme, we performed a simple power calculation as shown in Table 5 for the ASE spectrum of the free-running RSOA, which is transmitted from an ONU to the OLT on both the working and protection paths. The output ASE power from the free-running RSOA was measured at ~7.8 dBm and its spectrum is shown in inset (a) of Fig. 3. This ASE light was then spectrally sliced by two AWGs at RN and the power of the sliced light at 1545.5 nm was measured at about −20 dBm (refer to point (b) in Fig. 3). The insertion losses of the OC at ONU and the AWG at RN are 3 dB and 5 dB, respectively. Hence the AWG filtering loss is estimated to be about 20 dB. On the working path, after passing through a 20 km fiber, an OS and a CWDM, the received optical power at the power monitoring unit was about −25 dBm with the consideration of an optical gain of 15 dB from an EDFA. After being filtered by a CWDM, the L-band spectrum is shown in inset (c) of Fig. 3. On the protection path, the optical power received at the power monitoring unit was about −19.2 dBm. If no fiber failure occurs on both paths, the power received at the power monitor M_1 was about −18.2 dBm. These received ASE light powers are sufficiently high to serve as the "wake-up" signal to activate the associated transceiver in the OLT. The inset (d) of Fig. 3 shows the optical spectrum measured before the APD in the transceiver unit when the $RSOA_1$ was injected with a CW seeding light at 1545.5 nm with the injected power of −15 dBm. In this case, the power measured before the APD in the transceiver unit was about −12.5 dBm.

4. Energy-saving performance

To examine the energy-saving efficiency of the proposed energy-saving scheme, we have performed traffic simulation with 10 Gbit/s DS and 1.25 Gbit/s US transmissions. Both the ONU and its associated transceiver in the OLT are assumed to switch their operation modes simultaneously. The DS and US traffic are generated following a self-similar traffic model as described in

Table 5
Power calculation for US ASE light of single channel transmitted both on working path and protection path.

Filtering and insertion loss	Working path	Protection path
ASE output power from RSOA (dBm)	7.8	7.8
OC insertion loss at ONU (dB)	3	3
20 km (FF+DF) SMF loss (dB)	5	5
AWG insertion loss (dB)	5 × 2[a]	5 × 2[a]
AWG filtering loss at RN (dB)	20	20
OS insertion loss (dB)	1	1
CWDM insertion loss (dB)	0.8	
CWDM filtering loss (dB)	5	
OC insertion loss at power monitoring unit (dB)	3	3
Total filtering and insertion loss (dB)	47.8	42
C+L-band EDFA amplifier gain (dB)	15	15
Received power at monitor (dBm)	−25 −18.2[b]	−19.2

[a] "× 2" means the optical signal experiences the loss twice.
[b] A resultant power received at the corresponding monitor from both working path and protection path if no fiber failure occurs at two paths.

[25], where the resulting traffic stream is an aggregation of multiple sub-streams, each of which involves alternating Pareto-distributed ON/OFF periods with a shape parameter α and its corresponding Hurst parameter $H=(3-\alpha)/2$. In the implementation, an aggregation of 128 sub-streams is adopt and each sub-stream has shape parameter $\alpha=1.4$ for both ON and OFF periods. In the following discussion, each simulation result is the average over 10 simulations.

The total simulation duration T_{total} includes two parts: (1) the total duration T_{On} when an ONU is in the online state and (2) the total duration T_{Off} when an ONU is in the offline state. During the ONU online state, ONU has three operation modes (active, dozing and sleep). The ratio of the powers consumed in the active, dozing and sleep modes is assumed to be $P_A : P_D : P_S = 1 : 0.5 : 0.25$ [26].

In the following, we first examine the energy-saving efficiencies of our proposed 3-mode energy-saving scheme and compare it with the 2-mode energy saving schemes in [11–13] when an ONU is in the online state. Then the impact of ONU offline state on the energy-saving efficiency is also studied.

4.1. Energy-saving efficiency when an ONU is in online state

The energy-saving efficiency is defined as the percentage of energy saved in comparison to the situation where the system always stays in the active mode without using dozing and sleep modes. As shown in Eqs. (3) and (4), $\eta_{ES(On)}^{3M}$ denotes the energy-saving efficiency associated with our proposed 3-mode energy-saving scheme, and $\eta_{ES(On)}^{2M}$ is the 2-mode energy-saving efficiency associated with the schemes in [11–13] just with two operation modes (active and sleep). For both of the equations, the numerator of the 2nd term within the brackets represents the consumed power with the energy-saving scheme, whereas the denominator indicates the power consumption when the system always stays in the active mode (i.e. without energy saving). It is noted that when the ONU is in the online state, both the ONU and its associated transceiver in the OLT always experience the same mode transition, and both would stay in the same operation mode. Therefore, the energy-saving efficiencies in Eqs. (3) and (4) can be applied to both ONU and its associated transceiver in the OLT.

$$\eta_{ES(On)}^{3M} = \left(1 - \frac{T_D P_D + T_S P_S + (T_{On} - T_D - T_S) P_A}{T_{On} P_A}\right) 100\% \quad (3)$$

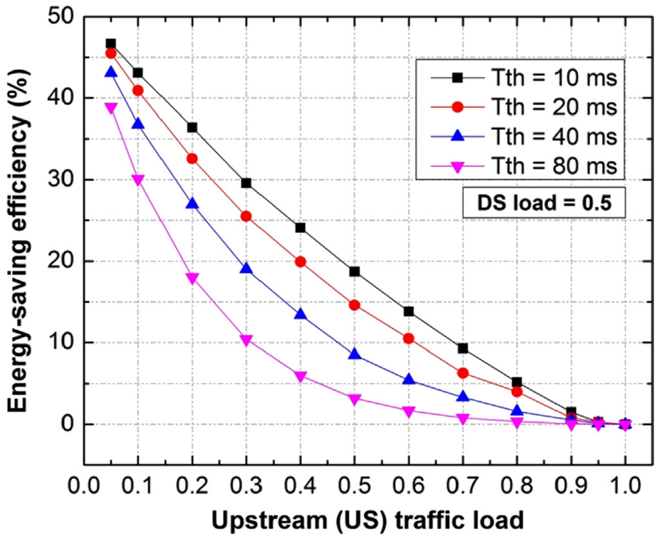

Fig. 6. Energy-saving efficiency as a function of US traffic load for different time thresholds by using our proposed energy-saving scheme.

$$\eta^{2M}_{ES(On)} = \left(1 - \frac{T_S P_S + (T_{On} - T_S)P_A}{T_{On} P_A}\right) 100\% \tag{4}$$

where T_{On} is the total duration when ONU is in online state, T_S is the total duration in the sleep mode, and T_D is the total duration in the dozing mode. We collected these time data from the simulation results.

We first studied the impact of the time threshold T_{th} on the efficiency $\eta^{3M}_{ES(On)}$ using our proposed energy-saving scheme. The results are shown in Fig. 6, where the DS traffic load is set to be 0.5 (i.e. 50%). As the time threshold T_{th} becomes larger, the efficiency $\eta^{3M}_{ES(On)}$ deceases. It is also observed that as the US traffic load increases, the efficiency $\eta^{3M}_{ES(On)}$ deceases almost lineally for the cases of $T_{th} = 10$ ms and 20 ms. But for the cases of $T_{th} = 40$ ms and 80 ms, the efficiency $\eta^{3M}_{ES(On)}$ decreases rapidly at the light traffic load and then slowly at the high traffic load (greater than 0.5). This is because that a larger time threshold keeps the system to stay in the active mode for a longer time before it can be switched into the dozing or sleep mode.

Fig. 7 shows the efficiency $\eta^{3M}_{ES(On)}$ versus the DS traffic load for different time thresholds T_{th} and different US traffic loads. As can be seen, the energy saving efficiency is almost independent of the DS traffic load for a given US traffic load and a given time threshold. This is due to the fact that in our proposed scheme, it is the US traffic load that decides the total energy-saving duration (including the dozing and sleep periods), while the DS traffic load only impacts the sleep period. However, the energy-saving contribution of the sleep mode is very low, which is verified by the simulation results shown in Fig. 8. Hence the DS traffic load has almost no influence on the energy-saving efficiency.

Fig. 8 compares the energy-saving efficiency of our proposed 3-mode scheme with that of the schemes in [11–13] which employ two operation modes (active and sleep) only. As shown in Fig. 8, our proposed scheme performs much better than the schemes in [11–13]. This is because, in addition to the sleep mode, our proposed scheme includes a dozing mode; whenever an ONU has no data to be sent for a period greater than T_{th}, both the ONU and its associated transceiver in the OLT are switched into the dozing mode, which allows a significant saving of power. (In the dozing mode, the associated transceiver in the OLT can continue to send DS data to the ONU.) However, the schemes in [11–13] do not include a dozing mode; an ONU and its associated transceiver in the OLT can enter into the sleep mode only if both of them have no data to be sent simultaneously for a period greater than T_{th},

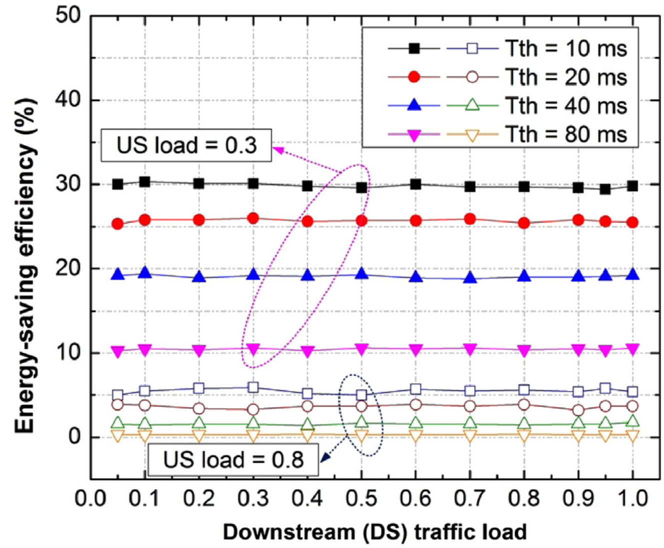

Fig. 7. Energy-saving efficiency versus DS traffic load under different time thresholds and different US traffic loads.

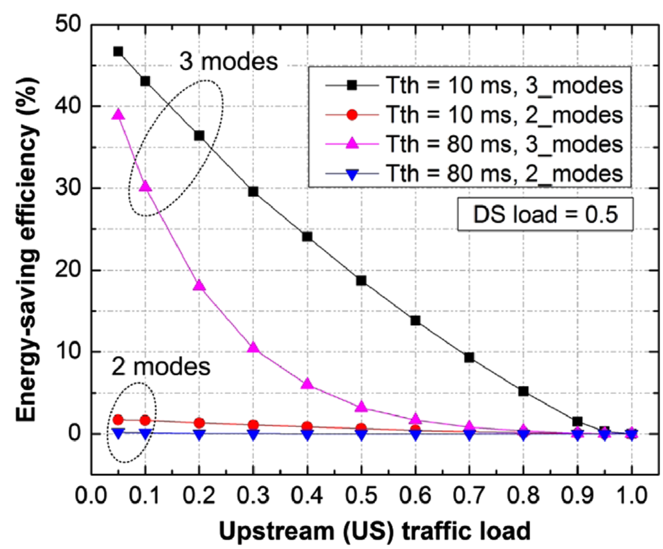

Fig. 8. Comparison of energy-saving efficiencies for our proposed 3-mode scheme and those 2-mode schemes in [11–13] under different time thresholds .

otherwise both of them stay in the active mode. The probability that both of an ONU and its associated transceiver in the OLT have no data to be sent for a period greater than T_{th} is extremely low, and hence the energy saving efficiency brought by the 2-mode scheme is very low (below 2% for $T_{th} = 10$ ms and below 0.2% for $T_{th} = 80$ ms). The simulation study has not only shown that our proposed 3-mode energy-saving scheme is very efficient, but also revealed that the energy saving mainly arises from the dozing mode, not from the sleep mode.

4.2. Impact of ONU offline state

We next study how the energy-saving efficiency is impacted when an ONU is in the offline state (e.g., shutdown) for a certain time. In such a case, the efficiency is expressed as

$$\eta^{3M}_{ES(Total)} = \left(1 - \frac{T_D P_D + T_S P_S + T_{Off} P_{Off} + (T_{On} - T_D - T_S)P_A}{T_{Total} P_A}\right) 100\% \tag{5}$$

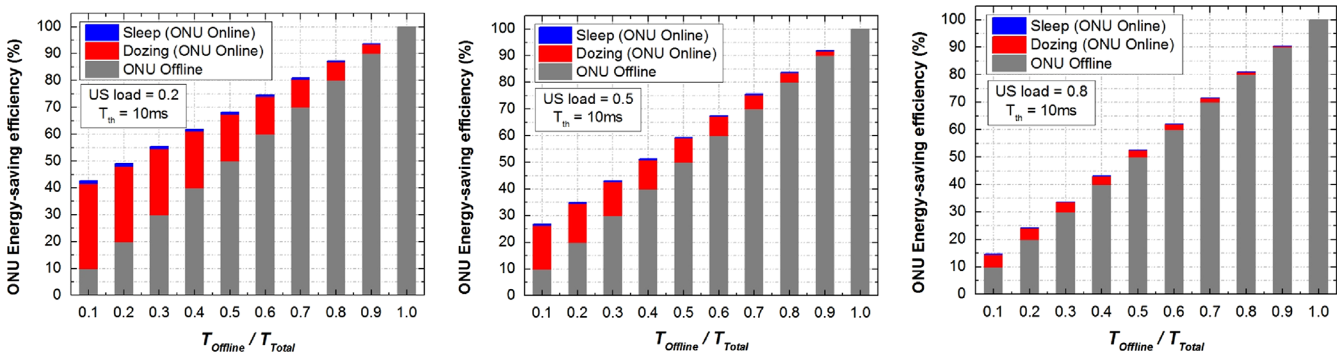

Fig. 9. ONU energy-saving efficiency versus $T_{Offline}/T_{Total}$.

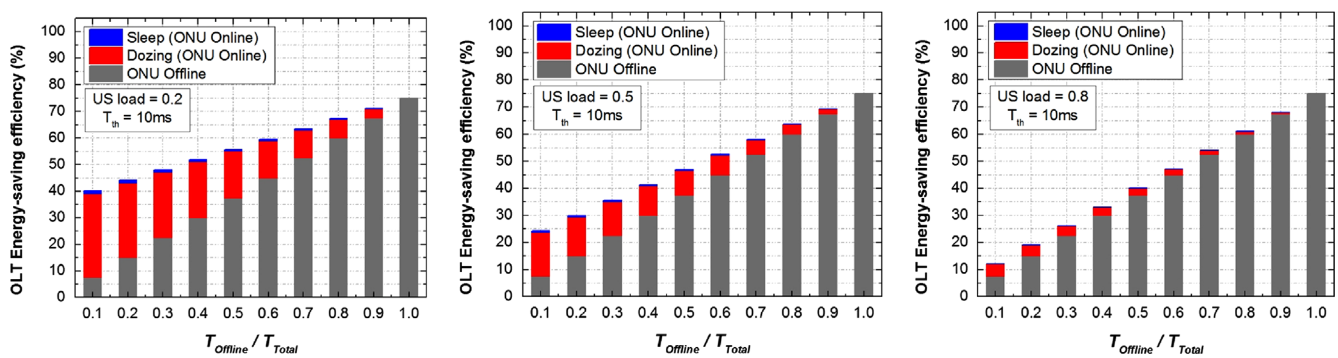

Fig. 10. OLT energy-saving efficiency versus $T_{Offline}/T_{Total}$.

where T_{Off} is the total when ONU is offline, and $T_{Total} = T_{On} + T_{Off}$ is the total simulation time.

The DS traffic load is set to be 0.5 and the time threshold T_{th} is 10 ms, while the US traffic load is chosen to be 0.2, 0.5 and 0.8. When an ONU is in the offline (i.e., ONU shutdown) state, the ONU is assumed to consume zero power (i.e., $P_{Off}^{ONU} = 0$), while in such a case the associated transceiver in OLT still stays in the sleep mode and is assumed $P_{Off}^{OLT} = P_S$. Figs. 9 and 10 show the ONU and OLT energy-saving efficiencies, respectively, when the ONU is offline (shutdown) for a certain ratio of time. As can be seen in Figs. 9 and 10, the energy-saving efficiency resulting from the ONU offline state increases proportionally to the increase in the time ratio $T_{Offline}/T_{Total}$. The saved power arising from the offline state for an ONU is larger than that for the associated transceiver in OLT. It is also observed that as the US traffic load increases, the energy-saving contribution of the sleep and dozing modes becomes smaller and smaller. This is because that it is more difficult for the ONU and its associated transceiver in the OLT to enter into the energy-saving modes as the US traffic load increases.

5. Conclusions

We have proposed and demonstrated a CLS-based centrally-controlled survivable and energy-saving WDM-PON with colorless ONUs. The proposed WDM-PON architecture can not only significantly reduce the energy consumption, but also deal with self-healing operation in various practical operation scenarios. Some detailed issues in different operation cases and the interaction of both schemes (i.e., logic signal synchronization issue) are also discussed. The feasibility of the proposed WDM-PON is verified experimentally with 10 Gbit/s DS and 1.25 Gbit/s US signals over 20 km SMF transmission. We have also studied the energy-saving efficiency performance by simulation. The results have not only shown that our proposed 3-mode energy- saving scheme performs much better than those 2-mode schemes, but also revealed that the energy saving mainly arises from the dozing mode, not from the sleep mode when the ONU is in the online state.

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