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An efficient energy-saving scheme incorporating dozing and sleep modes for CLS-based WDM-PONs with colorless ONUs

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Abstract: We propose and demonstrate an efficient energy-saving scheme incorporating dozing and sleep modes for WDM-PONs with centralized light sources (CLS). The novel scheme is based on simple power detection and local transmission request. Two logic control units are designed to switch the operation modes of the respective ONUs and their associated transceivers in the OLT. The scheme feasibility is experimentally verified with 10Gbit/s downstream and 1.25Gbit/s upstream transmissions. The simulation results reveal that the energy-saving of the ONUs in the online state mainly arises from the dozing mode, not from the sleep mode, while the energy-saving of the associated transceivers in the OLT is contributed mainly from the situation where ONUs are in the offline state.

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1. Introduction

With the emergence of bandwidth-intensive applications such as video on demand (VoD), high-definition internet protocol television, wavelength division multiplexed passive optical network (WDM-PON) with centralized light sources (CLS) in the optical line terminal (OLT) is highly recognized as a cost-effective solution to deliver gigabit broadband services to end-users [1,2]. There have been some reports on CLS-based WDM-PONs to realize source-free colorless optical network units (ONUs) [3–5], including wavelength reuse scheme [3] and wavelength seeding scheme [4,5]. Among them, the wavelength-seeding re-modulation technique by a reflective semiconductor optical amplifier (RSOA) with on-off keying (OOK) at the ONU appears to have a great potential for practical deployments, as 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 [4,5].

However, WDM-PONs employing CLS have a critical energy consumption problem. 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 not have upstream data in its output data queue all the time, and it may be offline (shut down) for certain periods in a day (e.g., in the early morning or at night). During the online period when there is neither downstream nor upstream data on a certain wavelength channel, the ONU and its associated transceiver in the OLT would naturally stop their signal transmission and enter into “sleep mode” to reduce energy consumption. Recently, several energy-saving schemes considering sleep mode for WDM-PONs were proposed [6–8]. 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 [6,7] or the amplified spontaneous emission (ASE) light generated by an RSOA in the ONU [8], which increases the system complexity. Moreover, these schemes only considered one energy-saving (i.e., sleep) mode, and hence their energy-saving efficiency is very low.

We here propose an efficient energy-saving scheme incorporating dozing and sleep modes for WDM-PONs with RSOA-based ONUs. Two logic control units are designed to switch the operation modes of the respective ONUs and their associated transceivers in the OLT, respectively. Both sleep and dozing modes are implemented in the ONUs, but only the dozing mode is incorporated in the transceivers of the OLT, since the receivers in the OLT need to be always “ON” to monitor the upstream ASE light power. Note that we use the upstream ASE light power as a “recovery request” signal. Thus, the proposed energy-saving scheme is based on simple power detection and local transmission request. It eliminates the modulation operation of any “recovery request” signal as in [6–8], but also requires no additional supervisory light source to generate the “recovery request” carrier as in [6,7]. More importantly, the proposed scheme incorporating two energy-saving modes (i.e., dozing and sleep) greatly improves the energy-saving efficiency for WDM-PONs.

2. Proposed energy-saving scheme and operation principle

The proposed energy-saving WDM-PON with \( N \) colorless ONUs is shown in Fig. 1. The OLT consists of \( N \) channel units, each having a transceiver and a control unit. In each channel unit, 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, the US receiver (RX) also acts as a monitor for detecting the US light power of the associated channel. The \( N \) DS signals of different wavelengths are multiplexed by a \( 1 \times N \) AWG and then transmitted to the remote node (RN) via a feeder fiber (FF). After being de-multiplexed by an AWG at the RN, the DS signals are sent to their corresponding ONUs via respective distribution fibers (DFs). In each ONU, a \( 2 \times 2 \) optical coupler (OC) is used to split the DS optical power into two parts: one is fed to a DS RX for 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.

![Fig. 1. Schematic diagram of the proposed energy-saving CLS-based WDM-PON architecture.](image)

To describe the proposed energy-saving scheme, we here focus on a pair of an ONU and its associated transceiver in the OLT. Two control units are designed as shown in Fig. 1, one in the ONU and the other in its associated transceiver in the OLT. All the input and output signals of both control units are represented by logic “0” and “1”. As shown in Fig. 2, from the viewpoint of the optical front-end transceiver’s (i.e., RX and TX) behavior, the ONU has three operation modes (i.e., active, sleep and dozing), while the associated transceiver in the OLT has two operation modes (i.e., active and dozing). The active mode means both TX and RX are “ON”; the sleep mode means both TX and RX are “OFF”; the dozing mode means that TX is “OFF” but RX “ON”. The sleep mode is not applied to the transceiver in the OLT since the RX in the OLT needs to continuously monitor the upstream ASE light power which acts as a recovery request.

![Fig. 2. State transition diagram for (a) an ONU and (b) the associated transceiver in the OLT.](image)

Referring to Fig. 1, as long as US transmission exists, the signal $q^{US}$ in the ONU is logic “1”, which keeps the US TX (i.e. RSOA) to stay in the “ON” state. While the US RX in the associated transceiver in the OLT is receiving the US data, a logic signal $P^{US} = 1$ is generated and thus the associated output signal $R$ is set to be logic “1”, which ensures the DS TX in the transceiver stays in the “ON” state too. When the DS RX in the ONU detects the DS carrier power, the signal $P^{DS}$ is set to be logic “1”, which in turn keeps the DS RX to stay in “ON” state. Hence in the above case, both the ONU and its associated transceiver in the
OLT are in the active mode. Thus the overall power consumption in the active mode is denoted by the full power $P_A$ (refer to the first two rows of Table 1).

**Table 1. Operation Modes of ONU and OLT According to DS and US Transmission States**

<table>
<thead>
<tr>
<th>Upstream (US)</th>
<th>Downstream (DS)</th>
<th>ONU operation mode</th>
<th>OLT operation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>Existing</td>
<td>Active</td>
<td>Active</td>
</tr>
<tr>
<td>Existing</td>
<td>No existing</td>
<td>Active</td>
<td>Active</td>
</tr>
<tr>
<td>No existing</td>
<td>Existing</td>
<td>Dozing (RSOA OFF, RX ON)</td>
<td>Active</td>
</tr>
<tr>
<td>No existing</td>
<td>No existing</td>
<td>Sleep (RSOA and RX OFF)</td>
<td>Dozing (TX OFF, RX ON)</td>
</tr>
</tbody>
</table>

Whenever 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 "$q_{US}=0$" generated by the US data queue turns off the RSOA in the ONU and triggers the ONU from the active mode to the dozing mode, where the RX in the ONU can continue to receive DS signal. This scenario can be found in many common applications where the DS traffic volume is extremely large while there is no US traffic temporarily, for example, video on demand and massive file download. Since the TX (i.e., RSOA) in the ONU is turned off, the overall power usage of the ONU in the dozing mode is reduced to a lower level $P_D$. Once the US RX of the corresponding channel in the OLT detects a drastic US power loss, a logic "$P_{US}=0$" is generated. Note that because the US RX is always “ON”, the associated transceiver in the OLT is still in the active mode (refer to the 3rd row of Table 1 and no. 1 state transition in Fig. 2(a)).

Under the scenario where the ONU is dozing but its associated transceiver in the OLT is in active mode, if no DS data exists in the DS data queue for a time period of $T_{th}$ (counted by an electrical timer, denoted as “T” in Fig. 1), the DS TX is turned off too and the associated transceiver in the OLT subsequently enters into the dozing mode (refer to no. 3 state transition in Fig. 2(b)). Due to the absence of the DS carrier, the DS RX in the ONU detects a drastic DS power loss and thus produces a logic signal "$P_{DS}=0$", which switches the ONU into the sleep mode (refer to no. 3 state transition in Fig. 2(a) and the 4th row of Table 1). In the sleep mode, both RX and TX (i.e., RSOA) in the ONU are turned off. Here we assume that the entire optical front-end transceiver and part of the back-end digital circuit are turned off when an ONU is switched to sleep mode. For instance, a sleeping ONU still maintains an ability to wake up upon the local US transmission request $q_{US}$, which can trigger the wakeup by itself. Hence, the sleep mode consumes the lowest overall ONU power of $P_S$, leading to the maximum power saving. In addition to the above online state where there is no DS and US traffic simultaneously, the sleep mode can also be applied to the ONU when it is in the offline state (e.g., shutdown). When the ONU is offline, the associated transceiver in the OLT stays in the dozing mode. Here the control signal designed for the DS RX in the ONU is $q_{US}+P_{DS}$ (refer to Fig. 1). It can be seen that the precondition of turning down the DS RX is "$q_{US}=0$", which indicates that the US TX (i.e., RSOA) has already been turned off before.

We assume that the transition from the sleep to the dozing mode in the ONU is prohibited based on a cognition that DS data could not be sent to a sleeping ONU that can be waked up only by its US data transmission request $q_{US}$. Hence, if there is any DS data packet arriving at the OLT for a specific ONU while that ONU is in the sleep mode, the DS data packet is discarded directly by the OLT. This assumption is reasonable because no DS data should be forwarded to a sleeping (or offline) ONU without the user-side request in access networks. With the assumption, the control signal $R$ for DS TX in a transceiver in the OLT is fed back to the input side. $R$ is expressed as $(R \times q_{DS}) + P_{ES}$ (refer to Fig. 1). From the expression, we know that when the control signal $R$ is logic “0” (i.e. the DS TX is off), the signal $R$ will not be changed to logic “1” by the signal $q_{DS}$; it can be changed to logic “1” if and only if there is the US ASE light received from the RSOA in the ONU (i.e., the logic signal $P_{ES}$ becomes “1”).
Once there is US data to be sent from the US data queue in a sleeping ONU or a dozing ONU, a resuming signal \( q_{US} = 1 \) is generated immediately to activate the RSOA in that ONU. Specifically, in case (i), when a dozing ONU is switched to the active mode (refer to no. 2 state transition paths in Fig. 2(a)), as there still exists DS carrier from the OLT, the RSOA in that ONU is wavelength-seeded and thus its US data can be sent to the OLT just after the turn-on time of the RSOA. Hence, the delay of the US data transmission is roughly equal to the turn-on time of the RSOA (e.g., 80 ns [9]). In case (ii), when a sleeping ONU is switched to the active mode (refer to no. 4 state transition paths in Fig. 2(a)), as there is no DS signal, the RSOA is not wavelength-seeded and its broadband ASE light is sent to the OLT. After being spectrum-sliced by the AWGs at the RN, the lights at wavelengths \( (\lambda + m \times \text{FSR}, m = \pm 1, \pm 2, \ldots) \) are transmitted to the OLT (FSR is the free spectral range of AWG), due to the cyclic spectral property of the AWG. Upon the US ASE light power being detected by the US RX of the corresponding channel, the \( P_{US} \) becomes “1” to activate the corresponding transceiver in the OLT to its active mode (refer to no. 4 state transition in Fig. 2(b)), which results in transmitting the DS light in the continuous wave (CW) to the associated ONU. After receiving the DS carrier, the associated ONU resumes the normal US data transmission and DS signal receiving. In such case, the total delay of the US data transmission includes not only the turn-on time of the RSOA (e.g., 80 ns [9]), but also a round trip time (propagation delay) between the OLT and that ONU (about 0.2 ms = (20 km \( \times \) 2)/(2 \( \times \) \( 10^5 \) km/s)) and the processing delay of digital circuits (e.g., \( \sim \) tens of ns). Here, the distance between an ONU and the OLT is assumed to be 20 km.

In addition, an un-cooled RSOA without the temperature controller can be used to reduce the ONU cost. As long as the downstream wavelength injected into the ONU is stabilized, the output wavelength of the un-cooled RSOA is also stabilized, since the RSOA is wavelength-seeded by the downstream wavelength. Therefore, whether a dozing ONU or a sleeping ONU is switched to the active mode, the total transmission delay of the newly-arrived US data is much less than 5ms, which will have a negligible impact on the Quality of Service (QoS) of the US traffic [10].

For the transmitter in the OLT, to obtain good transmission performance with a stabilized wavelength output, a cooled DFB-laser diode with the temperature controller is a potentially promising candidate in the practical deployment. We assume that the temperature controller (if applicable) of the transmitter in the OLT is not turned off during its dozing mode, so as to have a shorter overhead time of the mode switching from the dozing mode to the active mode. The laser turn-on time in the OLT is considered as the dominant overhead time of the mode switching. We have selected a conservative value of 600 ns [11] for laser turn-on time (i.e., wavelength stabilization duration), which will have a negligible impact on the QoS of the DS traffic.

3. Experimental setup and results

The feasibility of the proposed WDM-PON was experimentally studied by implementing the ONU-1 and its associated transceiver in the OLT. In the OLT, a CW light from a laser diode at 1545.5nm was modulated via a Mach-Zehnder modulator (MZM), which was biased at the transmission null point and driven by a 10Gbit/s data with a pseudo-random bit sequence (PRBS) with length of \( 2^{31} - 1 \) to generate DS non-return-to-zero (NRZ) OOK signal. The FF and DF are single mode fibers (SMFs) with lengths of 15km and 5km, respectively. The used 1 \( \times \) 16 AWG has a channel spacing of 100 GHz and a FSR of 31nm. In the ONU, one part of the DS signal was detected by an avalanche photodiode (APD) receiver; the other was amplified and re-modulated with 1.25Gbit/s \( 2^{31} - 1 \) PRBS US data via an RSOA. The un-cooled RSOA was biased at 30mA via a Bias-T circuit and the injected optical power was \(-15\)dBm. At these conditions, the RSOA was saturated with output power of 7.5dBm (i.e., output power = 22.5dB), and its 3dB modulation bandwidth was measured to be 1.5GHz.

As shown in Fig. 3, the bit-error-rate (BER) curves of the 10Gbit/s DS and 1.25Gbit/s US signals at 1545.5nm over 20km (FF + DF) SMF transmission were measured for different DS extinction ratios (ERs) and in the back-to-back (BTB) case. Error-free US transmission was
achieved with the DS ER of up to 5dB; an error floor at \(-7.5 \times 10^{-7}\) was observed for the US transmission when the DS ER was set to be 5.6. When the DS ER increased from 3dB to 5dB, the BER of the DS signal was improved, while the BER of the US signal became worst due to the higher interference from the DS signal. When DS ER was 5dB, the receiver sensitivities of the DS and US signals were \(-17.7\)dBm and \(-29.4\)dBm, and the power penalties for DS and US signals were about 0.6dB and 2.2dB, respectively. The power penalty for the DS is mainly due to the chromatic dispersion, while for the US it is attributed to the backscattering noise.

![Graph showing measured BER performances of the 10Gbit/s DS and 1.25Gbit/s US signals over 20km SMF transmission for different DS ERs and in BTB case.]

We also measured the optical power and the ASE spectrum of the free-running RSOA at three different points on the US path. The output ASE power from the free-running RSOA was measured at about 9dBm and its spectrum was labeled as (a) in Fig. 4. This ASE light was then spectrally sliced by an AWG at RN and the output power was measured at \(-19dBm\). After passing through a 20km fiber, an AWG and a circulator, the received optical power at the US RX was about \(-29dBm\), whose spectrum is labeled as (b) in Fig. 4. This ASE light power is sufficiently high to activate the associated transceiver in the OLT as the “wake-up” signal. Figure 4 also shows the optical spectrum (labeled as (c)) measured before the US RX when the RSOA was injected with a CW seeding light at 1545.5nm with the injected power of \(-15dBm\). In this case, the power measured before the US RX was about \(-12.5dBm\).

![Graph showing optical spectrum (a) before US RX with ASE light, (b) after being spectrally sliced by an AWG, and (c) wavelength-seeding spectrum at 1545.5nm.]

Fig. 4. (a) ASE spectrum of free-running RSOA; (b) the spectrum after being spectrally sliced by an AWG at RN; (c) wavelength-seeding spectrum at 1545.5nm.
4. Energy-saving performance

To examine the energy-saving efficiency, we performed traffic simulations with 10Gbit/s DS and 1.25Gbit/s US transmissions. To obtain an accurate and realistic performance analysis, it is very important to simulate the system behavior with appropriate traffic injected into the system. There is an extensive study showing that most network traffic flows can be characterized by the properties of self-similarity and long-range dependence (LRD) [12]. To generate self-similar traffic, the DS and US traffic are generated by using the traffic model described in [12,13], where the resultant traffic stream is an aggregation of multiple sub-streams, each of which involves alternating Pareto-distributed ON/OFF periods. (Note that the traditional exponential distribution possesses no LRD property [12].) In the simulation, 128 sub-streams is aggregated and each sub-stream has shape parameter $\alpha = 1.4$ for both ON and OFF periods. In the ON period, Ethernet packets whose size is uniformly distributed from 64 to 1518 bytes are transmitted sequentially, and the inter-frame gap (IFG) between two adjacent packets is fixed to be 20 bytes. In the OFF period, no packet is generated. The following result is the average over 10 simulations.

As shown in Eq. (1) and Eq. (2), the energy-saving efficiencies $\eta_{ONU}$ and $\eta_{OLT}$ are 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. For both of the equations, the numerator of the 2nd term within the brackets represents the power consumed by the ONU and the associated transceiver in the OLT with the proposed energy-saving scheme, whereas the denominator indicates the power consumption when the system always stays in the active mode (i.e. without energy saving). The total simulation duration $T_{total}$ includes two parts: 1) the total duration $T_{onu}^{on}$ when an ONU user is in the online state and 2) the total duration $T_{onu}^{off}$ when an ONU user is in the offline state. During the ONU online state, ONU has three operation (active, dozing and sleep) modes. In our simulations, we assume that the ratio of $T_{onu}^{off}$ over $T_{total}$ is 0.2 (Note that this value can be varied according to the practical scenarios). Thus $T_{onu}^{on}$ is assumed to be the 80% of $T_{total}$ . When an ONU user is in the offline (e.g., ONU shutdown) state, the ONU is assumed to consume zero power (i.e., $P_{onu}^{off} = 0$) and meanwhile the OLT is definitely in the dozing mode. Thus, we obtain $T_{onu}^{off} = T_{D(OH)}^{off}$. From the scheme description in Section 2, we know that the total duration $T_{onu}^{on}$ when ONU is in the sleep mode is equal to the total duration $T_{D(OH)}^{on}$ when the associated transceiver in the OLT is in the dozing mode, namely $T_{onu}^{on} = T_{D(OH)}^{on}$. We collected the data of $T_{total}$, $T_{onu}^{on}$ and $T_{D(OH)}^{on}$ from the simulation results, and $T_{onu}^{off}$ is the total duration when the ONU is in the dozing mode. The ratio of the powers consumed for an ONU in the active, dozing, and sleep modes is assumed
to be $P_{\text{A}}^{\text{onu}} : P_{\text{D}}^{\text{onu}} : P_{\text{s}}^{\text{onu}} = 1:0.5:0.25$ [11], while the ratio of the powers consumed for the associated transceiver in the OLT in the active and dozing mode is also assumed to be $P_{\text{A}}^{\text{olt}} : P_{\text{D}}^{\text{olt}} = 1:0.5$.

In Fig. 5, the notation “ONU offline” and “ONU online” in the right side indicates that an ONU user is in the offline and online states, respectively. We first set the DS traffic load to be 0.5 (50%). As shown in Fig. 5, the energy-saving efficiency $\eta_{\text{ONU}}$ is much larger than the $\eta_{\text{OLT}}$, which becomes more distinct when the ONU is online. This is because the transceiver in the OLT can enter into the dozing mode only if there have been neither US nor DS data to be sent simultaneously for a period greater than $T_{\text{th}}$, otherwise it stays in the active mode. The probability that both US and DS data traffic simultaneously enter into the OFF period greater than $T_{\text{th}}$ is extremely low, and hence the $\eta_{\text{OLT}}$ is very low (e.g., below 1% for $T_{\text{th}} = 10$ ms and below 0.2% for $T_{\text{th}} = 80$ ms) when the ONU is online. It is also observed that as the threshold time $T_{\text{th}}$ becomes larger, the efficiencies in the ONU online state decrease. It is because that a larger $T_{\text{th}}$ keeps the system to stay in the active mode for a longer time before it can be switched into the dozing or sleep mode. With the increase of US traffic load from 0.2, 0.5 to 0.8 while the DS traffic load remains 0.5, the efficiencies $\eta_{\text{ONU}}$ and $\eta_{\text{OLT}}$ in the ONU online state decease in Fig. 5.

![Fig. 5. Energy-saving efficiencies in different operation modes for (a) an ONU and (b) the associated transceiver in the OLT versus US traffic load under different time thresholds.](image1)

![Fig. 6. ONU energy-saving efficiency versus DS traffic load under different time thresholds and different US traffic loads when the ONU is in the online state.](image2)
Figure 6 also shows the ONU energy-saving efficiency versus the DS traffic load for different time thresholds $T_{th}$ and different US traffic loads when the ONU is in the online state. As can be seen, the energy saving efficiency of an online ONU is almost independent of the DS traffic load for a given US traffic load and a given time threshold. This is because that it is only the US traffic load that decides how long the ONU is in the energy-saving (e.g., dozing or sleep) modes. Only if the US traffic is in OFF period, the DS traffic load can bring about the sleep mode for ONU or the dozing mode for OLT, but the corresponding energy-saving contribution in such cases is negligibly low (which is verified by the simulation results shown in Fig. 5).

Hence, we can conclude that the energy-saving for ONU in the online state mainly arises from the dozing mode, not from the sleep mode, while the energy-saving of the OLT is contributed mainly from the situation where the ONU is in the offline state.

5. Conclusion

We have proposed an efficient energy-saving scheme incorporating dozing and sleep modes for a CLS-based WDM-PON. The novel scheme is based on simple power detection and local transmission request. Two logic control units are designed to switch the operation modes of the respective ONUs and their associated transceivers in the OLT. The scheme feasibility is experimentally verified with 10Gbit/s DS and 1.25Gbit/s US signals over 20km SMF. The simulation results have verified the effectiveness of the proposed energy-saving scheme.

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