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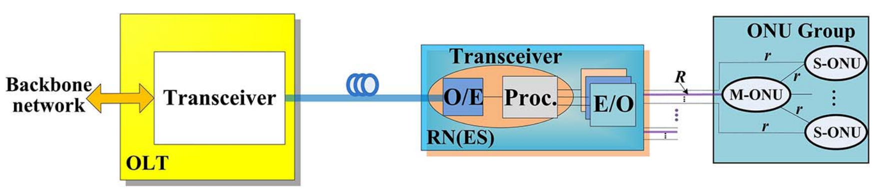

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An Efficient Energy-Saving Scheme Based on Grouping of ONU for Optical Access Network Using Electronic Switch

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Abstract: We propose an efficient energy-saving scheme by dividing the optical network units (ONUs) into groups composed of one master-ONU (M-ONU) and several slave-ONUs (S-ONUs). The S-ONUs are primarily selected to communicate with the M-ONU and, second, with the remote node (RN), which can reduce the usage of high-power ports at the RN and subsequently decrease energy consumption. It is demonstrated that obvious energy-saving effects can be achieved, and moreover, the energy-saving efficiency can be further improved by expanding the capacity of the links between RN and M-ONUs and properly selecting the scale of the ONU group.

Index Terms: Optical access network, energy efficiency, energy saving.

1. Introduction

Because of the explosive growth in the demand for bandwidth, the optical network has been extensively deployed and subsequently followed by a crucial problem of increasing energy consumption [1]. Therefore, the energy savings of the optical access network (OAN) has attracted increasingly more attention in recent years because a large amount of the total energy consumption of the whole optical network is consumed by the optical access network part [2]–[4]. Several schemes, such as energy-efficient optical network unit (ONU), sleeping/dozing mode, and passive optical network (PON), have been proposed to reduce the energy consumption of optical access network [5]–[8], and moreover, some standards for power-saving of OAN have been released [9]–[11].

The optical access network using electronic switch (ES-OAN) is a type of novel optical access network architecture that has emerged lately. In ES-OAN, an electronic switch (ES) is used to replace the passive optical splitter, which can relax the link budget constraint, and there is no need to compensate the dispersion at ONUs. For these reasons, the ES-OAN is an attractive solution to address the future 40 Gbps access based on direct modulation and is one potential energy-saving technology for future 40 Gbps fiber access networks [12]. However, the study on

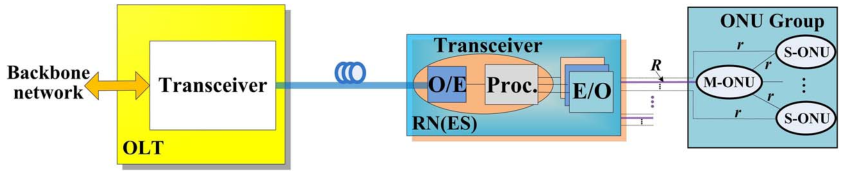

Fig. 1. Architecture of the proposed ONU-grouped ES-OAN.

the energy-saving properties of ES-OAN is rare, and there has been no thorough investigation on the energy consumption and energy-saving efficiency of ES-OAN, which motivates further investigations.

In this paper, we propose a novel energy saving scheme by dividing the ONUs into several groups, each of which includes one master-ONU (M-ONU) and several slave-ONUs (S-ONUs). The energy-saving effect is performed by reducing the usage of high power ports at the remote node (RN), in virtue of connecting S-ONUs with M-ONU with low power modules according to the traffic volume. The results demonstrate that the ONU-grouped scheme can obviously reduce the energy consumption of ES-OAN, with respect to those of conventional ES-OAN and OAN with optical splitter (OS-OAN).

2. Principles and Analysis

Fig. 1 shows the architecture of the proposed ONU-grouped ES-OAN. Differing from the OS-OAN, the ES-OAN includes an active remote node (RN) which adopts ES to store and forward the incoming packets from the OLT and ONU ports. The RN exchanges packets with the OLT through a transceiver and adopts specialized ports to establish point to point connections with ONUs. The transceiver converts the optical signal from OLT into electrical and adopts a processor to compensate the fiber dispersion. Although the ES-OAN uses active components at RN, the ONUs do not need to consume any energy to compensate the optical dispersion, the energy efficiency has been improved obviously with respect to the architectures adopting the WDM and TDM technologies [12]. n ONUs form a group, wherein one ONU that maintains connection with RN all the time is called as M-ONU, while the residual ONUs are called S-ONU. In the ONU group, the M-ONU use $n-1$ optical modules to connect with S-ONUs. Each S-ONU has two optical ports: One is used to connect with M-ONU, and the other one is used to connect with RN. At any moment, only one of the S-ONU optical ports is working for data transmission. Which of the two optical ports is "ACTIVE" is controlled by the instantaneous traffic load information. In such a case, no complicated physical connection switching is needed, and the total energy consumption is not increased, with respect to the case using one optical port ONU, and moreover, the network installation and maintenance costs would not be increased greatly. With respect to the conventional ES-OAN, the energy consumption of M-ONU is larger, because that more than 1 optical ports are "ACTIVE," while the energy consumption of single S-ONU is not increased. However, since no energy is consumed to compensate dispersion, no physical connection switching is needed, and some high-power RN optical ports are turned off, the total energy consumption is decreased, and the energy efficiency would be much better than the conventional ES-OAN and other OAN schemes.

In the proposed scheme, when the total traffic load of an ONU group is lower than the allowed bit rate of the link between RN and the M-ONU (R), the link between RN and M-ONU can satisfy the bit rate requirement of transmission, and then the S-ONUs are not necessary to directly communicate with RN. Consequently, $n-1$ high-power RN ports can be turned off, and some energy can be saved correspondingly. In this case, the downstream data is firstly received by RN and then forwarded to M-ONU, and finally, the M-ONU forwards the data to S-ONUs through low-power ports. Similarly, the upstream data from S-ONUs is first collected by M-ONU and then transmitted to RN which aggregates and transmits the upstream data to OLT. On the other hand, when the total traffic of the group is relatively high, some S-ONUs need to directly communicate with RN to avoid congestion. Over all, as long as not all ONUs are working at the maximum bit rate, there may always be some S-ONUs that do not need to communicate with RN directly, and some energy can still be saved. For the sake of simplicity, here the average normalized traffic loads of ONUs are assumed to be identical, and noted as $\sigma \in [0, 1]$ ($\sigma = V/r$, where V is the instantaneous traffic, r is the capacity of the links connecting S-ONUs with RN or M-ONU), the total number of ONUs in the ES-OAN is N. The power consumption of single M-ONU and single S-ONU can be respectively described as

$$P_{\text{M-ONU}} = (n_a \times P_{\text{optical-port}} + P_{\text{fiber/cable-port}}) \times (1 + \alpha) \quad (1)$$

$$P_{\text{S-ONU}} = (P_{\text{optical-port}} + P_{\text{fiber/cable-port}}) \times (1 + \alpha) \quad (2)$$

where $P_{\text{optical-port}}$ and $P_{\text{fiber/cable-port}}$ stand for the power of the optical modules connecting with the RN ports and that of the ports connecting with the users, respectively, n_a is the number of M-ONU optical ports working at "ACTIVE" state, which is defined as (3), and the factor α stands for the additional power consumption of other components, such as the inefficient AC/DC converter and voltage regulator

$$n_a = \begin{cases} n, & \text{when } \sigma \le \frac{1}{n} \\ i, & \text{when } \frac{1}{i+1} < \sigma \le \frac{1}{i}, i \in 1, 2, \ldots n-1. \end{cases} \quad (3)$$

For the conventional ES-OAN, its total power consumption can be written as

$$P_{\text{conventional}} = P_{\text{OLT}} + P_{\text{RN-transceiver}} + P_{\text{RN-port}} \times N + P_{\text{ONU}} \times N. \quad (4)$$

While in the proposed ONU-grouped ES-OAN, the total power consumption is

$$P_{\text{ES-ONU}} = P_{\text{OLT}} + P_{\text{RN-transceiver}} + P_{\text{RN-port}} \times N_a + P_{\text{M-ONU}} \times N_M + P_{\text{S-ONU}} \times (N - N_M). \quad (5)$$

In these equations, $P_{\text{RN-port}}$ is the power of RN ports that connect with ONUs, which is much higher than the power of corresponding ONU port $P_{\text{optical-port}}$, $N_M = [N/n]$ denotes the number of M-ONUs, where the operation $[x]$ means rounding to the nearest integer equaling or greater than x, and $N_a = N_M \times (n - n_a + 1)$ stands for the number of "ACTIVE" RN ports that directly connect with ONUs.

3. Illustrative Numerical Results

For the purpose of numerical simulations, we take one 40 Gbit/s ES-OAN architecture with a typical split ratio of 1 : 32 for example. At the OLT end, a 40 G transceiver is used to aggregate the upstream data from RN and simultaneously send the downstream data to RN. The RN function is performed by an electronic switch, which consists of a 40 G transceiver and 32 ports. The RN transceiver includes functions of electronic/optical conversion and signal-processing, while the RN ports are used to connect with ONUs. Each S-ONU is composed of two optical modules through one of which the S-ONU can communicate with RN directly or indirectly, a fiber/cable port that connects with the user, and some other components that consume additional 30% power. While the M-ONU contains n optical modules, one of which is connected with RN constantly, and the residual modules are used to connect with S-ONUs. For the purpose of comparison, an OS-OAN and a DWDM-OAN are also considered here, their detailed topologies have been presented in [12]. The downstream (DS) and upstream (US) bit rates for and the typical power values of the state-of-the-art commercially available components for the three types of OAN are shown in Table 1.

Fig. 2(a) shows the total power consumption of OS-OAN, DWDM-OAN and ONU-grouped ES-OAN with different group scales. Here the capacity of the link between RN and M-ONU is set to be identical to that of the link between M-ONU and S-ONU, namely $R = r$. It is obvious that the proposed scheme can reduce the power consumption when the average normalized traffic volume of each ONU is lower than 0.5. Specifically, when $\sigma \le 1/n$, the total traffic volume of the ONU group does not exceed the link capacity R, all S-ONUs can indirectly communicate with RN through M-ONU, $n - 1$ high power RN ports can work at "OFF" state for the ONU group,

TABLE 1

Power consumption of components [12]

Type	OLT	RN	ONU
ES-OAN DS:40Gbit/s US:40Gbit/s	40G transceiver:6 W	40G transceiver:6W Each RN port:3W	Optical module:1 W 1000 base T/F:1 W Others (factor α):30%
OS-OAN DS:40Gbit/s US:20Gbit/s	Optical module:1.5W System of Chip:24W Others:30%	Optical amplifier:40W	Optical module:1.5W 1000 base-T PHY:0.75W SOC: 16W Others(factor α): 30%
DWDM-OAN DS:40Gbit/s US:40Gbit/s	Power per L2 switch GbE port: 3W TEC per laser:0.5W TEC for WDM:5W	TEC for WDM filter:5W	Optical module:1W 1000Base-T/F:1W TEC for Laser:0.5W Other: 30%

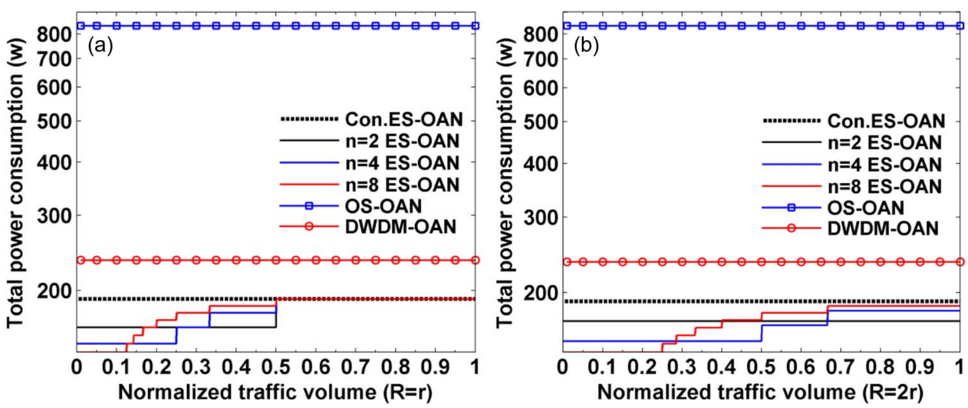

Fig. 2. Power consumption comparison among the OS-OAN (blue-squared), DWDM-PON (red-circled), conventional ES-OAN (dashed), and ONU-grouped ES-OAN, for the case of (a) $R = r$ and (b) $R = 2r$.

and then some power can be saved for the whole network. When $\sigma > 1/n$, the total traffic volume of the group is larger than R, the M-ONU cannot support all S-ONUs simultaneously. In this case, the number of S-ONUs that M-ONU can support decreases gradually as the increase of σ. If $1/n < \sigma \leq 1/(n-1)$, M-ONU can support $n-2$ S-ONUs, if $1/(n-1) < \sigma 1/(n-2)$, M-ONU can support $n-3$ S-ONUs, and so on. Finally, M-ONU cannot support any S-ONU when $\sigma > 0.5$. Under such a scenario, the states of all RN ports in the whole network are "ACTIVE," and the network works as the conventional architecture. It is worth mentioning that the larger n can induce more power-saving when $\sigma \leq 1/n$, but the ONU group would collapse more easily, since the region in which the M-ONU can support all S-ONUs is narrower.

To further improve the power saving efficiency of the ONU-grouped scheme, we propose to expand the capacity of the link between RN and M-ONU, while those of the links connecting S-ONUs with RN and M-ONU are not changed. Under such a scenario, even the average normalized traffic of S-ONUs reaches 1, $k-1$ S-ONUs can be supported by M-ONU if $R = kr$ ($k = 1, 2, \ldots$). Fig. 2(b) presents the numerical results for the case of $k = 2$. Here the power value of the RN ports that connect with M-ONUs is increased to 3.5 W for the increased processing capacity. It is apparent that the power-saving efficiency has been improved greatly with respect to the case of $k = 1$ [see Fig. 2(a)]. This is because the traffic volume range in which the M-ONU can support all or a portion of S-ONUs has been enhanced by k times, subsequently more high-power RN ports can be turned off, and correspondingly, more energy is saved.

Next, to further confirm the feasibility of the proposed scheme, we investigate the energy efficiency for the scenario with adaptive traffic variation. Fig. 3(a) shows the daily online ratio of the

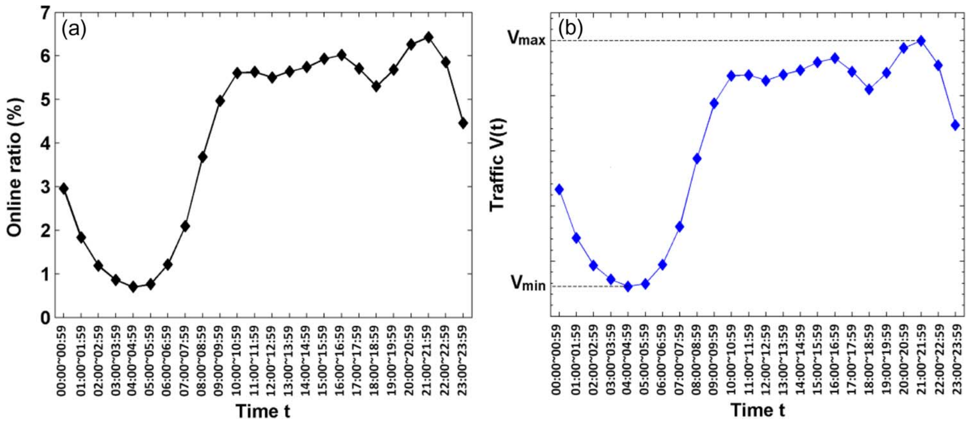

Fig. 3. (a) Daily Internet usage in China April 2013/September 2013. (b) Daily traffic model.

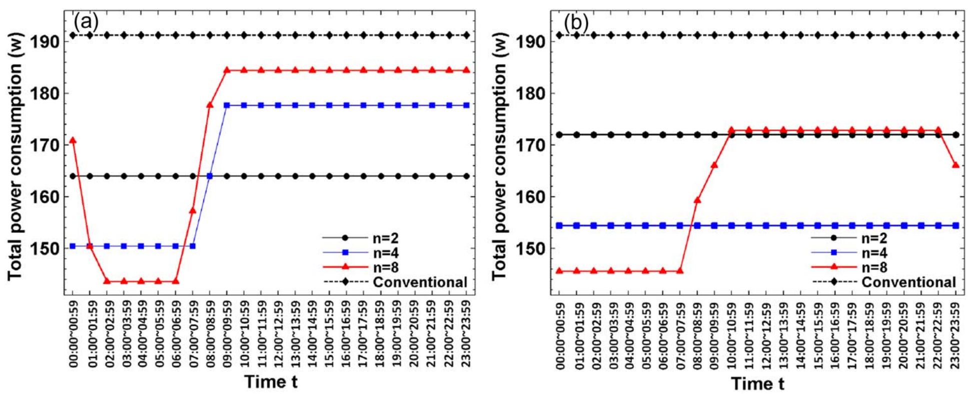

Fig. 4. Daily power consumption of the conventional ES-OAN (dashed-diamond) and ONU-grouped ES-OAN for the cases of (a) $R = r$ and (b) $R = 2r$.

Chinese Internet usage, which is a statistical data obtained from more than 1.5 million network stations in the six months from April 1 to September 30 in 2013 [13]. It is shown that there are only 6.43% users are online in the busiest hour. According to the method in [14], we can obtain a traffic model as shown in Fig. 3(b). Based on this, we can estimate the corresponding normalized traffic for ES-OAN. In a general network, since only a portion of users not all users are online at the same time, such that the daily maximum traffic of users is usually smaller than the capacity to avoid congestion. Here, the capacity of ES-OAN is set to $2V_{\max}$ (actually, it may be larger); namely, the network can afford about 13% users being simultaneously online.

Fig. 4 shows the daily power consumption of the proposed scheme for the cases of $R = r$ and $R = 2r$. Apparently, the proposed scheme can work in a relatively low power state in the low traffic time interval, and moreover, the power consumption can always be reduced to some extent, which is because that some S-ONUs need not always communicate with RN directly in a whole day. Nevertheless, the power consumption of conventional ES-OAN keeps at a constant and relatively high level. On the other hand, when the capacity of the link between RN and M-ONU has been doubled, a more obvious energy-saving effect can be observed, like that shown in Fig. 4(b), which is in line with the results in Fig. 2.

To more systematically investigate the influence of the scale of ONU group on the energy efficiency, we have presented the energy efficiency factor η versus n in Fig. 5. The energy efficiency factor here is defined as the ratio of the energy consumption of the ONU-grouped scheme and that of the conventional ES-OAN. From the definition, it is obvious that the larger the factor, the worse energy efficiency. In addition to the cases of $R = r$ and $R = 2r$, another

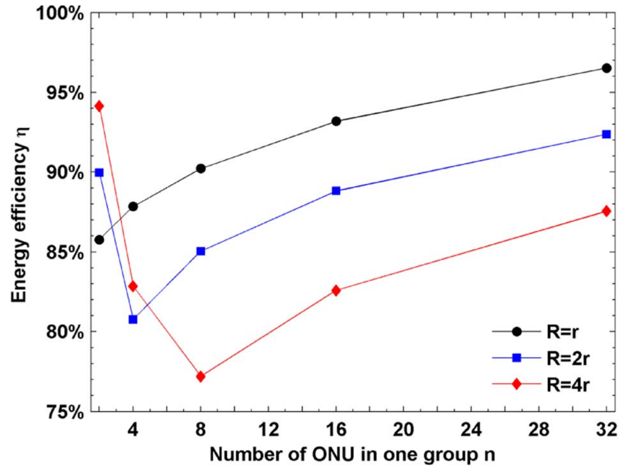

Fig. 5. Energy-saving efficiency of the ONU-grouped ES-OAN. In the case of $R = 4r$, the power value of the RN ports is set to 4W for the increased processing capacity.

case of $R = 4r$ is also presented. For the case of $R = r$, the energy efficiency gets worse and worse gradually as the group scale increase. This is because that as the increase of n, the traffic range in which the M-ONU can support all S-ONU is narrow, and in some traffic regions the power consumption of the case with a larger n is higher than those cases with a relatively smaller n (see the results for $n = 4$ and $n = 8$ in Fig. 2). For the cases of $R = 2r$ and $R = 4r$, when the value of n is relatively small, the energy efficiencies may be lower than the case of $R = r$, because of the increasing usage number of the high power RN ports. However, an apparent energy efficiency improvement can be observed, when the value of n increases further. In addition, to guarantee the universality of the proposed scheme, we have also done some simulations with the traffic models reported in [14], and the results are similar.

Over all, with proper selection of the scale of ONU group, obvious energy-saving efficiency can be achieved, and expanding the capacity of links between RN and M-ONUs can further improve the energy saving efficiency. The ONU-grouped energy-saving scheme may also be suitable for the other OAN architectures, such as TDM-PON, WDM-PON, *etc*. Studies on these issues may be found in our future works.

4. Conclusion

A novel energy-saving scheme for optical access network using electronic switch has been introduced. In this scheme, the ONUs are divided into groups including one M-ONU and several S-ONUs. According to the traffic volume, S-ONUs are preferred to communicate with M-ONU and secondly to communicate with RN, which can decrease the usage of "ACTIVE" high-power ports at RN and subsequently reduce the energy consumption of the whole system. Simulation results demonstrate that an obvious energy-saving effect can be observed with respect to the conventional ES-OAN and OS-OAN, and the energy efficiency can be obviously improved by expanding the capacity of the links between RN and M-ONUs. This work provides a potential way to implement the energy-efficient OAN.

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