Balancing Energy Efficiency and Device Lifetime in TWDM-PON Under Traffic Fluctuations

Jialong Li, Zhizhen Zhong, Nan Hua, Xiaoping Zheng, and Bingkun Zhou

***Abstract*—Energy-efficient time- and wavelength-division multiplexed passive optical network has been intensely investigated. However, conventional schemes aimed at energy efficiency may bring about repeated power-state transitions between sleep mode and active mode, resulting in periodic device-temperature cycling and frequent wavelength reassignment, which will greatly deteriorate network quality of service. These side effects become non-trivial when traffic fluctuates sharply as expected in the future. In this letter, we propose a wavelength-postponed-switching-off (WPS) strategy to reduce power-state transitions by means of postponing the power-off of redundant wavelengths. Redundant wavelengths represent wavelengths that are supposed to be powered off by conventional schemes when traffic declines. Illustrative results show that, the WPS strategy can provide a balanced performance of both energy efficiency and device lifetime, while decreasing service interruption caused by turning ON or OFF the equipment.**

***Index Terms*—Device lifetime, ONU migration, energy efficiency, TWDM-PON.**

I. INTRODUCTION

PASSIVE Optical Network (PON) is widely implemented in optical access networks for its passive features, cost efficiency, and scalability. To meet the rapid bandwidth increase driven by real-time video streaming, Time- and Wavelength- Division Multiplex PON (TWDM-PON) has been proposed and regarded as a promising solution for optical access networks in the near future [1].

Many energy-saving algorithms have been proposed in previous studies [2]–[4]. However, these methods, which only focus on energy efficiency, may bring about many side effects. Two main drawbacks, lifetime degeneration, and Optical Network Unit (ONU) migrations, should be highlighted here. On one hand, when a heating device, such as a transmitter equipped in the line card, is turning on and off repeatedly, thermal fatigue may occur in the materials, thus leading to a significant lifetime degeneration [5]. The experiment in [6] points out that the temperature swing turns out to be the dominant factor in device lifetime deterioration. On the other hand, ONU migrations occur along with wavelength reconfiguration. If the migration transpires, incoming packets have to be buffered or dropped until the reconfiguration is completed, which causes delay or loss of packets and degrades the Quality of Service (QoS). Meanwhile, emerging traffic patterns, like tidal traffic [7], will make this problem even worse. Therefore, conventional energy-saving-oriented algorithms should be revisited carefully to cope with these new challenges.

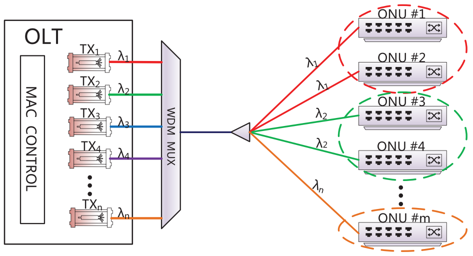

Fig. 1. TWDM-PON architecture.

In this letter, a Wavelength-Postponed-Switching-off (WPS) strategy, realized by postponing the power-off of redundant wavelengths, is first introduced. Simulation results show that our strategy can provide a balanced performance of both energy efficiency and device lifetime, and decrease service interruptions caused by ONU migrations when turning on or off the equipment.

II. SYSTEM MODEL

The TWDM-PON architecture is shown in Fig. 1. For simplicity, only downstream wavelengths are depicted in the diagram. Tunable transmitters and receivers are equipped in ONU and Optical Line Terminal (OLT). As presented in Fig. 1, ONU #1 and #2 are assigned with wavelength λ_1. It is the same case with ONU #3 and #4.

A. ONU Migration

ONU migration, as introduced in [8], is performed at the cost of service interruption. Generally, average ONU migration delay ranges from 200 ms to 1600 ms [9]. We use the migrated traffic amount to evaluate the influence scope of ONU migration. To maintain continuous service, ONU migrations should not occur frequently. Therefore, ONU migrations should be operated wisely to make the best use of bandwidth, while avoiding migration interruptions.

B. Device Lifetime

The logarithm of the lifetime is inversely proportional to the device working temperature. The impact caused by temperature cycling is modeled by Coffin-Manson Equation [10]. According to the model presented in [11], the overall failure rate of the device can be expressed as below.

$$\gamma = \frac{T_{on}}{T_{total}}\gamma_{on} + \frac{T_{off}}{T_{total}}\gamma_{off} + \frac{f_{trans}}{N_f T_{total}} \tag{1}$$

Failure rate, denoted as γ here, represents the frequency of failure events per hour and the device lifetime can be

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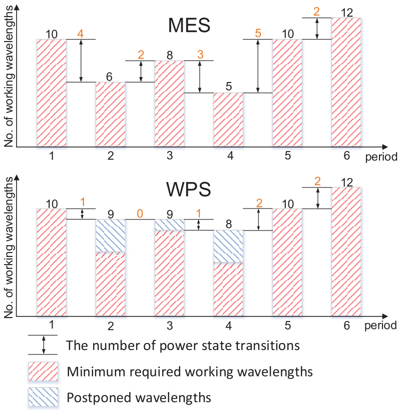

Fig. 2. An example of WPS.

calculated by $1/\gamma$. T_{on} and T_{off} are the amount of time that a device stays in active state and sleep state, respectively. γ_{on} is the failure rate when the device in active state, and γ_{off} is the failure rate in sleep state. f_{trans} is the number of power state transitions, and N_f is the number of temperature cycles achieved by the device before a failure occurs. We assume that failure events are statistically independent.

III. WAVELENGTH-POSTPONED-SWITCHING-OFF (WPS) STRATEGY

In Section III-A, we propose WPS strategy to determine the number of working wavelengths. According to these results, we provide an algorithm on how to migrate the traffic in Section III-B. The combination of the two parts will provide practical operations in network reconfigurations.

A. What is the Number of Working Wavelengths

Conventional energy-efficient approaches, like Maximum-Energy-Saving (MES) strategy, aimed at minimizing the number of working wavelengths.[1] This can be regarded as the bin-packing problem, and we can not get an optimal solution in polynomial time. Here, we further use a heuristic algorithm, First Fit Decreasing (FFD) [12] to solve it. FFD is described below: sort ONUs in descending order of traffic load in each period,[2] and then associate them with the first wavelength with sufficient remaining bandwidth. We can estimate the minimum number of required working wavelengths each period by FFD.

Due to these side effects, device lifetime deterioration and ONU migration, we propose the WPS, which is described in Algorithm 1. *The main idea of WPS is to postpone the power-off of some redundant wavelengths for several periods even when the traffic load declines*. Compared to MES which employs as few working wavelengths as possible, WPS reserves some wavelength resource for future possible rapid traffic fluctuations.

In Algorithm 1, *Postponed wavelengths* mean wavelengths that are supposed to be powered off in MES strategy, but are set to be working in our WPS strategy. *Postponed time* further describes the postponed working time of postponed wavelengths. A simple example is depicted in Fig. 2. The maximum number of postponed wavelengths is 3, and postponed time is 5 periods. The number of working wavelengths of MES and WPS in each period is annotated in the graph. During this postponed time, the number of power-state transitions by MES is 16, while only 6 by WPS.

Algorithm 1 WPS Strategy

```
Initialize:
  $e \leftarrow$ the total number of periods;
  $m \leftarrow$ the maximum number of postponed working wavelengths;
  $p \leftarrow$ postponed periods;
  $m_0 \leftarrow$ required wavelengths in period 0;
  $G \leftarrow \emptyset$, the set containing the number of working wavelengths in each period;
  $d \leftarrow 0$;
while $d < e$ do
  for $i = 1 \rightarrow p$ do
    calculate the required wavlengths $m_1$ by FFD in period $d + i$;
    if $m_0 > m_1$ then
      $r \leftarrow min(m_0 - m_1, m)$; /* postponed working wavelengths */
    else
      $r \leftarrow 0$;
    end if
    $m_1 \leftarrow m_1 + r$; /* the actual use of wavelengths in period $d + i$ */
    $m_0 \leftarrow m_1$; /* update $m_0$ for next period */
    $G.add(m_1)$;
  end for
  $d \leftarrow d + p$; /* next cycle */
end while
return $G$;
```

B. How to Migrate the Traffic

The ONU migration model is described below:

Given:

- C: capacity of a single wavelength.
- A: the number of working wavelengths in current period.
- N, W: the total number of ONUs and wavelengths, respectively.
- b_i: required bandwidth of ONU i in current period.
- x_{ij}: predefined matrix element, which is one if ONU i associates with wavelength j in previous period, else zero.
- z_j: predefined matrix element, which is one if wavelength j is active in previous period, else zero.

Variables:

- x'_{ij}: binary decision variable, which is one if ONU i belongs to wavelength j in current period.
- z'_j: binary decision variable, which is one if wavelength j is active in current period.

Optimize:

$$Minimize \sum_{i=1}^{N}(1 - \sum_{j=1}^{W} x_{ij}x'_{ij})b_i \tag{2}$$

$$Subject\ to \sum_{i=1}^{N} x'_{ij}b_i \le C \quad \forall j \in [1, W] \tag{3}$$

$$1 - \prod_{i=1}^{N}(1 - x'_{ij}) = z'_j \quad \forall j \in [1, W] \tag{4}$$

$$\sum_{j=1}^{W} z'_j \le A \tag{5}$$

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[1] We use the number of active wavelengths in each period to capture the energy consumption.

[2] In our simulation, we reconfigure the wavelength assignment every one hour. So there are 24 periods in one day.

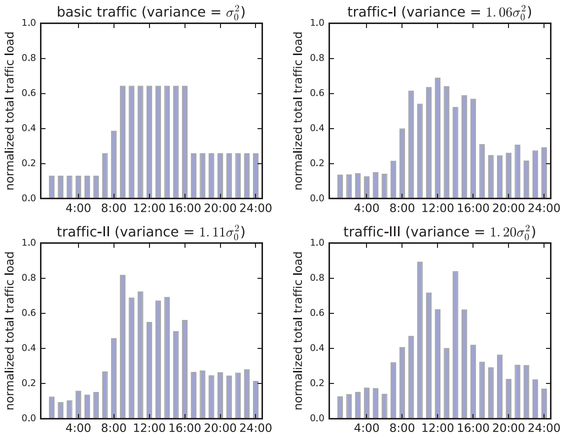


Fig. 3. Different fluctuant traffic load.

Equation (2) tries to find the optimal wavelength reconfiguration. Constraint (3) ensures traffic load in any wavelength should not exceed the capacity. Equation (4) indicates a wavelength is working when any ONU is assigned with it. Constraint (5) limits the number of working wavelength.

This problem can be transformed to the multiple knapsack problem [13], which is already proved to be NP-hard and not suitable for large networks. Therefore, we further develop a heuristic algorithm, named Wavelength Reassignment Algorithm (WRA) here, to obtain a sub-optimal answer. WRA is described in Algorithm 2. When traffic load increases, more wavelengths are activated and light-load ONUs are relocated preferentially. As traffic load declines, light-load wavelengths are powered off and the corresponding ONUs are reconfigured in descending order.

Algorithm 2 Wavelength Reassignment Algorithm (WRA)

```
Initialize:
    $m_0 \leftarrow$ the number of working wavelengths in previous period;
    $m_1 \leftarrow$ the number of working wavelengths in current period;
    $U \leftarrow \emptyset$, the set containing pre-migrate ONUs;
    $V \leftarrow$ the set consisting of working wavelengths in previous period;
1: sort wavelengths in $V$ in descending order of current load;
2: if $m_0 < m_1$ then
3:     add $m_1 - m_0$ idle wavelengths to $V$;
4: else
5:     remove $m_0 - m_1$ of the least-load wavelengths from $V$ and add the corresponding ONUs to $U$;
6: end if
7: for each wavelength in $V$ do
8:     if total traffic load exceeds the capacity then
9:         reset this wavelength and add ONUs in descending order of load as many as possible;
10:        put the residual ONUs to $U$;
11:    end if
12: end for
13: sort ONUs in $U$ in descending order;
14: for each ONU in $U$ do
15:     add ONU to the max-load wavelength with sufficient remaining bandwidth, remove this ONU from $U$;
16: end for
17: while $U \neq \emptyset$ do
18:     add the max-load ONU in $U$ to the least-load wavelength, remove a least-load ONU to $U$ which makes the load in this wavelength not exceed the capacity;
19:     sort $U$ in descending order and turn to step 14;
20: end while
21: return $V$;
```

IV. ILLUSTRATIVE EVALUATIONS

A. Simulation Setup

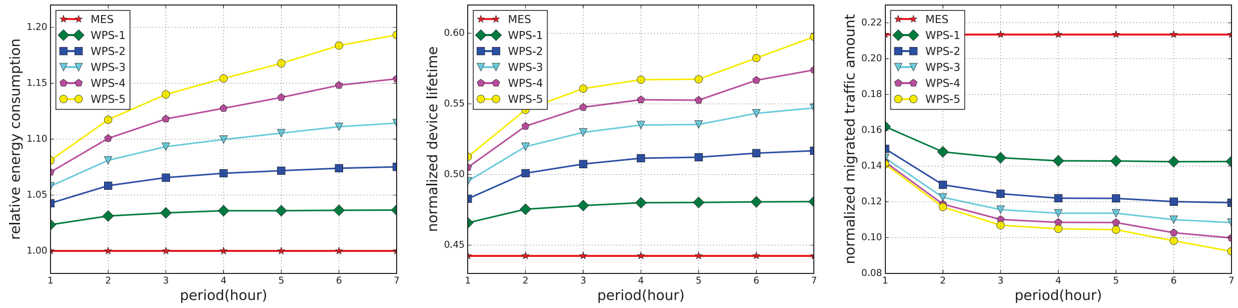
In our system configurations, the TWDM-PON system consists of 64 ONUs and 32 wavelengths. The bandwidth of a wavelength is 10 Gbit/s and the maximum data rate in one ONU is not more than 5 Gbit/s. We investigate the lifetime of line cards in OLT side. In accordance with Cisco [14], the lifetime of a line card is approximately 116052 hours. In sleep state, device lifetime is 3-fold more than in working state. The number of cycles N_f is set to 10^4 according to the experiments in [15] and [16].

We develop a hybrid C++/Python simulation platform to evaluate the performance. To generate different fluctuant traffic loads conformed to the reality, three kinds of traffic load are generated in the following way. First, a basic traffic matrix is set up for each ONU in one day, with high bandwidth requirement in the daytime while relatively low at night. Then, we insert different levels of randomness into the basic traffic matrix to generate different kinds of traffic fluctuations. We use the variance of total traffic load in the observed time to describe the network traffic fluctuations. The variance of basic traffic is σ_0^2 and other three fluctuant traffic's variances are $1.06\sigma_0^2$, $1.11\sigma_0^2$, and $1.20\sigma_0^2$ compared to the basic traffic, respectively. The upper left graph in Fig. 3 shows the basic traffic matrix and the residual subgraphs represent three different fluctuant traffic load. The observed time is 72000 hours (for simplicity, only 24 hours are presented in the figure).

B. Performance Analysis

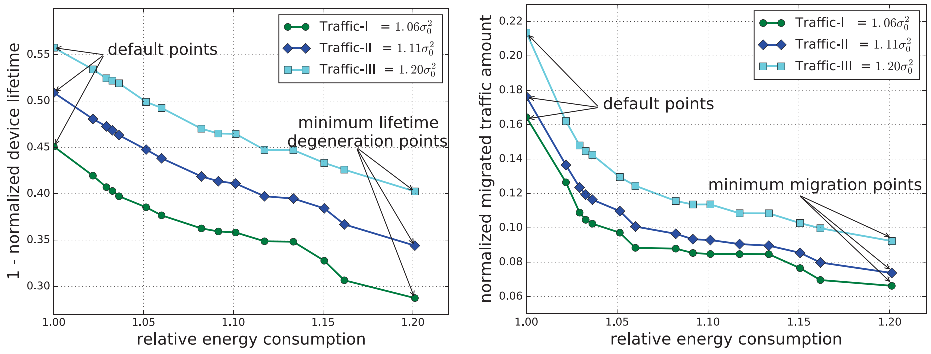
Fig. 4(a-c) show energy consumption, device lifetime, and ONU migrations when MES and WPS are applied to traffic-III. The n in WPS (equals 1,2,3,4,5) represents the maximum number of postponed wavelengths. We can find that energy consumption increases with the increment of the maximum number of postponed working wavelengths and postponed time. WPS consumes more energy than MES since extra working wavelengths are not powered off immediately. According to Fig. 4(b), a line card's lifetime reduces more than 50% when energy efficiency is optimized. Owing to less frequent power state transitions, WPS$-$5 mitigates the lifetime degeneration by 17% when postponed time is 7 hours, which means the device can work for more 18568 hours with our previous assumptions. In terms of the migrated traffic amount, MES triggers average 21% migrated traffic in each period while only 9% occurs when WPS$-$5 is applied based on Fig. 4(c). Due to less frequent power state transitions, ONUs are moved to a new wavelength in a lower possibility compared to MES.

Fig. 5 demonstrates the system's performance when traffic fluctuates differently. In Fig. 5, default points show performance achieved by MES while minimum migration/lifetime degeneration points present the performance achieved by WPS$-$5 with 7 hours' delay. Device lifetime can be reduced by 45%, 51% and 56% at default points compared to continuously working state while WPS alleviates the lifetime degeneration by 16%, 15%, and 17% at minimum lifetime degeneration points, respectively. As for the migrated traffic amount, average 16%, 18%, and 21% migrated traffic occurs in each period while low to 6%, 7%, 9% is achieved by WPS at minimum migration points. When the amount of migrated



(a) (b) (c)

Fig. 4. Comparison between energy consumption (a), device lifetime (b), and migrated traffic amount (c) with a different number of postponed working wavelengths and postponed periods under traffic-III.



(a) (b)

Fig. 5. Trade-off between energy consumption and lifetime deterioration (a), energy consumption and migrated traffic amount (b) under different traffic fluctuations.

traffic declines, service interruptions will be reduced, which improves the QoS performance. It can be noticed that when traffic fluctuates more rapidly, the device lifetime deteriorates more severely and more migrated traffic occurs. It is because more fluctuant traffic load results in larger differences in the number of working wavelengths between two periods, thus leading to more power state transitions and ONU migrations. WPS reduces these differences by postponing the power-off of extra working wavelengths, which alleviates the device lifetime deterioration as well as reduces ONU migration simultaneously.

V. CONCLUSION

Conventional energy efficiency schemes may deteriorate the device lifetime and cause huge ONU migration in the TWDM-PON-enabled access networks. The situation becomes more severe when rapidly-fluctuant traffic transpires. We propose a simple and effective scheme to balance these aspects. Simulation results demonstrate that our strategy can achieve longer lifetime and less migrated traffic with reasonable energy compromise.

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