Design of WDM PON With Tunable Lasers: The Upstream Scenario

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***Abstract*—Tunable lasers are potential upstream optical light generators for wavelength-division-multiplexing (WDM) passive optical network (PON), which is a promising solution for next-generation broad-band optical access. The wavelength provisioning flexibility of tunable lasers can increase the admissible traffic in the network as compared to wavelength-specific lasers. Generally, the broader the lasers' tuning ranges, the more the traffic can be admitted to the network. However, broad tuning range requires sophisticated technology, and probably high cost. To achieve the optimal tradeoff between the admissible traffic and the cost, we investigate the relationship between lasers' tuning ranges and the network's admissible traffic and then design WDM PON by selecting lasers with proper tuning ranges for the upstream data transmission. Specifically, we focus on addressing two issues under three scenarios. The two issues are: how to admit the largest traffic by properly selecting lasers, and how to admit given upstream traffic using lasers with tuning ranges as narrow as possible. The three scenarios are: full-range tunable and wavelength-specific lasers are available, limited-range tunable lasers are available, and the exact number of lasers with specific tuning ranges are given.**

***Index Terms*—Admissible traffic, tunable laser, tuning range, wavelength-division-multiplexing (WDM) passive optical network (PON).**

I. Introduction

WAVELENGTH-DIVISION-MULTIPLEXING (WDM) passive optical network (PON), which efficiently exploits the large capacity of optical fibers, is becoming one promising next-generation broad-band optical access solution [1]–[3]. As compared to time-division-multiplexing (TDM) PON such as Ethernet PON [4] and gigabit PON (GPON) [5], WDM PON increases its capacity by utilizing optical devices with multiwavelength provisioning capability. Many WDM PON architectures with different optical devices have been proposed to provision multiple wavelengths [6]–[8].

To provision multiple wavelengths for upstream transmission, WDM PON can be realized in two major architectures, depending on the placement of optical light generators [9]. The first scheme is to equip optical network units (ONUs) with lasers for their own upstream traffic transmission. The lasers are placed at the ONU side. An alternative scheme is to utilize lasers at the optical line terminal (OLT) side to supply seed light for upstream transmission. The unmodulated light supplied by OLT is first transmitted down to ONUs and then modulated and reflected back by ONUs. Instead of lasers, reflective receivers and modulators are equipped at ONUs to realize colorless ONUs [10]. The reflective modulator can be based on reflective semiconductor optical amplifier combined with an electroabsorption modulator [11]. Since the signal and seed lights are transmitted in opposite directions on the same wavelength, this kind of network may need to consider the effect of optical reflection, including Rayleigh backscattering, which limits the maximum network reach and largest channel bit rate [12]. In this paper, we focus on the former architecture, which is simpler, more reliable, and is potentially able to achieve a higher loss budget and larger bit rate [9], [13].

There are three major classes of optical source generators depending on the wavelengths generation capability, namely, wavelength-specific sources, wavelength-tunable sources, and multiwavelength sources [14]. A wavelength-specific source emits only one specific wavelength, e.g., the common DFB/distributed Bragg reflector (DBR) laser diode (LD), or the vertical-cavity surface-emitting LD. A multiple-wavelength source is able to generate multiple WDM wavelengths simultaneously, including multifrequency laser, gain-coupled DFB LD array, and chirped-pulse WDM. Besides multiwavelength sources, a wavelength-tunable source can generate multiple wavelengths as well [15]. However, it can only generate one wavelength at a time. Tunable lasers can employ many technologies such as DFB array, sampled grating DBR, external cavity diode laser etalon, etc. Different technologies may yield different tuning ranges. Among these three kinds of optical source generators, wavelength-specific lasers or wavelength-tunable lasers are usually adopted. Multi-frequency lasers are currently not favored owing to their high cost.

As compared to wavelength-specific lasers, wavelength-tunable lasers have two main benefits [16]. First, from the multiple access (MAC) layer's point of view, in the case of wavelength-specific lasers, one wavelength channel is utilized by a fixed set of lasers, and thus the statistical multiplexing gain cannot be exploited for traffic from lasers using different wavelength channels. In the case of wavelength-tunable lasers, the wavelength tunability of tunable lasers facilitates statistical multiplexing of traffic from a larger set of lasers, thus potentially yielding better system performance. Second, for network operators, tunable lasers offer advantages such as simple inventory management and reduced sparing cost.

In this paper, we equip each ONU with one tunable laser for its own upstream data transmission. We try to exploit the tunable lasers' merit of statistical gain in the MAC layer. Each

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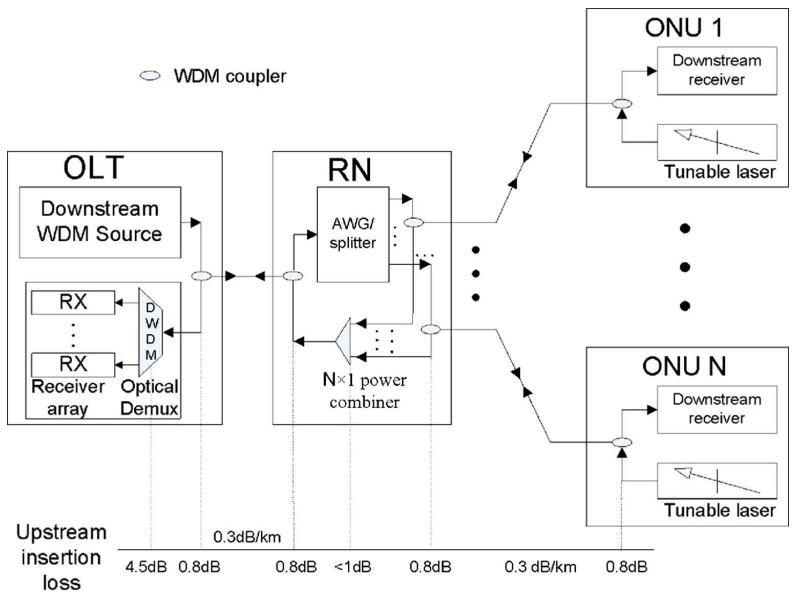

Fig. 1. WDM PON architecture.

employed tunable laser can be tuned to a specific set of wavelengths. One wavelength may be shared by more than one ONU in the TDM fashion. The hybrid WDM/TDM property of the upstream transmission makes it possible to exploit statistical gain among traffic from different ONUs. The upstream transmission is detailed as follows. Tunable lasers at ONUs first send out the modulated signal to the remote node (RN). RN employs an $N \times 1$ wavelength-inselective power combiner to multiplex the upstream signal from N ONUs onto the fiber connected to OLT. The signal multiplexed in both the time and wavelength domain is then transmitted to OLT. At the OLT side, one wavelength demultiplexer and a receiver array are employed to receive the upstream signal.

Different tuning ranges of tunable lasers may lead to different traffic statistical gain and hence resulting in different admissible traffic. However, to the best of our knowledge, the issue of determining tuning ranges of tunable lasers has not been addressed so far. To this end, we try to properly select tuning ranges of lasers to achieve the best network performance from the MAC layer's perspective in this paper. Intuitively, the broader the tuning ranges of lasers are, the higher statistical gain can be exploited, and the more traffic can be admitted to the network. However, lasers with broader tuning ranges require more sophisticated technology and thus incur higher cost than those with narrower tuning ranges. One arising problem is to achieve the optimal tradeoff between tuning ranges of lasers and the admissible traffic of the network. This problem is equivalent to that of selecting lasers with tuning ranges as narrow as possible to admit the maximum traffic or given upstream traffic.

Specifically, this paper focuses on addressing the design problem under the following three scenarios.

1) Assume full-range tunable lasers are available, and full-range tunable lasers enable the network to admit the largest amount of traffic. However, equipping all ONUs with full-range tunable lasers may introduce high cost. To reduce the cost of lasers, can we decrease the number of full-range tunable lasers in the network, and at the same time still admit the same amount of traffic?
2) Assume limited-range tunable lasers with different tuning ranges are available, and each ONU can select a laser with any available tuning range; how do we select lasers properly to enable the network to admit as much traffic as possible or admit given upstream traffic?
3) Given an exact number of lasers with specific tuning ranges, how do we assign these lasers to ONUs to admit given upstream traffic? The solution to this problem can be applied to address the system upgrading issue under the condition that only a subset of ONUs can be selected and upgraded due to the limited budget.

The rest of the paper is organized as follows. Section II describes the network architecture and system model. We employ a bipartite graph to describe the relationship between lasers and wavelengths. Section III discusses the problem of reducing the number of full-range tunable lasers without decreasing the admissible traffic. Section IV discusses the problem of selecting lasers with proper tuning ranges to maximize the admissible traffic or to admit given upstream traffic. Section V discusses the problem of assigning given lasers with specific tuning ranges to ONUs to admit given upstream traffic. Section VI presents concluding remarks.

II. Network Architecture and System Model

A. Network Architecture

In this paper, we only consider the upstream scenario and use different wavelengths for upstream and downstream transmission. Fig. 1 illustrates the considered network architecture. Each ONU is equipped with one tunable laser for its own upstream data transmission. Each laser can be tuned to a set of wavelengths. The wavelength sets tuned by different lasers can be the same, overlapped, or disjoint. Some wavelengths may be shared by more than one ONU. In this way, the statistical gain among traffic of ONUs that share wavelengths can be exploited.

The upstream-modulated signals are first transmitted from ONUs by tunable lasers to RN. After receiving the upstream signal, RN uses WDM couplers to separate the upstream signal from the downstream signal and then employs an $N \times 1$ wavelength-inselective power combiner to multiplex the upstream signal from the total of N ONUs onto the fiber connected to OLT. The output signal of the power combiner is multiplexed in both the time and wavelength domain. RN will then transmit the multiplexed signal to OLT. OLT employs one wavelength demultiplexer and a receiver array to receive the upstream signal. Both the number of output ports of the demultiplexer and the number of receivers are equal to the total number of wavelengths used in this network. As shown in Fig. 1, the whole upstream transmission link consists of four WDM couplers (around 0.8 dB insertion loss each), one power combiner (less than 1 dB insertion loss), one dense WDM demultiplexer (around 4.5 dB insertion loss), and optical fibers (0.3 dB/km insertion loss). Thus, the total insertion loss except the transmission fiber is around 8.7 dB.

This network architecture has two main characteristics. First, each ONU is equipped with one tunable laser for its own upstream transmission. Tunable lasers' merit of flexible wavelength provisioning can be exploited to improve the system performance. Second, at RN, the upstream and downstream signals are separated by WDM couplers and then routed differently within RN. In this way, the upstream and downstream wavelength assignment problems can be addressed individually. A power combiner/splitter can multiplex the upstream signals with low insertion loss. Owing to the wavelength-inselective property of power combiner/splitter, the upstream wavelength assignment does not need to consider the wavelength routing capability of RN. However, the power combiner/splitter is unsuitable for downstream signal distribution because of its high splitting loss. To achieve a higher downstream power budget, RN may adopt wavelength-selective devices with low insertion loss, such as arrayed waveguide gratings to distribute downstream signal. Then, the downstream wavelength assignment needs to consider the wavelength routing capability of RN. Hence, separating upstream signals from downstream signals at RN adds more flexibility in addressing the upstream wavelength assignment problem.

B. System Model

We employ a directed bipartite graph to describe the relationship between lasers at ONUs and upstream wavelengths [17]. Denote set L as the set of lasers, and set W as the set of wavelengths. An edge exists between vertex l in set L and vertex w in set W if laser l can be tuned to wavelength w. Denote $\{L \cup W, E_{LW}\}$ as the bipartite graph formed by the laser set L and the wavelength set W. Fig. 2 shows examples of bipartite graphs for four ONUs and two wavelengths. In Fig. 2(a), all lasers can be tuned to either of the two wavelengths. In Fig. 2(b), each laser can be tuned to one wavelength only.

The traffic that can be transmitted on each laser depends on the transmission data rate of the laser and the traffic of other lasers. Generally, the traffic transmitted by a laser cannot exceed the laser's maximum transmission data rate, and the total traffic

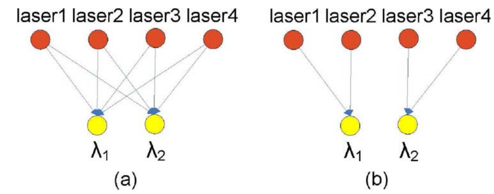

Fig. 2. One example of upstream transmission in WDM PON. (a) Full-range tunable lasers and (b) limited-range tunable lasers.

transmitted on a wavelength cannot exceed the capacity of the wavelength.

With respect to the abstracted bipartite graph, we define the rate of vertex l $(l \in L)$ as the traffic rate of laser l, and the rate of vertex w $(w \in W)$ as the traffic rate transmitted on wavelength w. Then, the rate of l $(l \in L)$ is limited by the data rate of lasers, and the rate of w $(w \in W)$ is limited by the capacity of the wavelength. Assume the maximum data transmission rate of each laser and the capacity of each wavelength are all equal to C. Then, the rate of each vertex is upper bounded by C.

Based on these constraints, we introduce the definition of *admissible traffic* in terms of rates of vertices in the laser set L.

Definition 1: Denote vector $R = [r_1, r_2, \ldots, r_{|L|}]^T$ as the traffic rates of lasers, where r_i is the rate of laser i. R is said to be admissible if it satisfies the constraint: for any subset $\mathcal{L}$ of the laser set L $(\mathcal{L} \subset L)$ with the corresponding set of wavelengths set $\mathcal{W}$ tunable by lasers in set $\mathcal{L}$, the sum of traffic rates of lasers in set $\mathcal{L}$ is bounded by the sum of capacities of wavelengths in set $\mathcal{W}$, i.e., $\sum_{l \in \mathcal{L}} r_l \leq |\mathcal{W}|C$.

For the laser example, as shown in Fig. 2(a), traffic R is admissible if

$$\begin{cases} r_i \leq C & \forall i \\ \sum_{i=1}^{4} r_i \leq 2C \end{cases}.$$

For the laser example, as shown in Fig. 2(b), traffic R is admissible if

$$\begin{cases} r_i \leq C & \forall i \\ r_1 + r_2 \leq C \\ r_3 + r_4 \leq C \end{cases}.$$

Having defined admissible traffic, we shall next design WDM PON to maximize the admissible traffic or to admit given upstream traffic.

Generally, the design problem can be formulated as a dual problem. First, given lasers with certain tuning ranges, how do we select the lasers with proper tuning ranges to maximize the admissible traffic? Second, given upstream traffic to be admitted, how do we enable the network to admit the traffic rate by using lasers with tuning ranges as narrow as possible, i.e., the lowest cost? We define the tuning range of a laser as the set of wavelengths to which the laser are tuned. We assume lasers with broader tuning ranges are costlier. Regarding the abstracted bipartite graph, the problem is equivalent to configuring the edges between the set of vertices L and the set of vertices W.

In this paper, we will discuss the design issue under three scenarios of tunable lasers.

1) Full-range tunable lasers and wavelength-specific lasers are commercially available. Each ONU can be equipped

with either full-range tunable laser or wavelength-specific laser. Here, full-range tunable lasers refer to lasers that can be tuned to any wavelength in the wavelength set W, and wavelength-specific lasers refer to lasers that can be tuned to only one wavelength.

2) Limited-range tunable lasers with different tuning ranges are commercially available. Each ONU can be equipped with any of these commercially available lasers with certain tuning wavelengths. Limited-range tunable lasers refer to lasers that can be tuned to a subset of the wavelength set W.
3) The exact number of lasers with specific tuning ranges are given. The network operator has purchased N lasers with specific tuning ranges for N ONUs. Then, each ONU will be assigned with one of these given lasers.

The network in the first scenario with full-range tunable lasers will admit the largest amount of traffic. In the last scenario, the ONU has the least flexibility of laser selection. We shall next detail the designing process.

III. Design of WDM PON With Full-Range Tunable Lasers and Wavelength-Specific Lasers

In this section, we discuss the design problem under the condition that full-range tunable lasers and wavelength-specific lasers are available. The network operator can equip ONUs with either full-range tunable lasers or wavelength-specific lasers.

If all lasers at ONUs are full-range tunable, the bipartite graph $\{L \cup W, E_{LW}\}$ is then fully connected, as shown in Fig. 2(a). Under the condition that all ONUs are full-range tunable, the upstream traffic rate R is admissible if it satisfies the following constraint:

$$\begin{cases} r_i \le C & \forall i \\ \sum_{i=1}^{|L|} r_i \le |W|C \end{cases}.$$

When the number of wavelength $|W|$ is below the number of lasers $|L|$, increasing $|W|$ enables the network to admit more traffic. When $|W|$ is increased above $|L|$, further increase of $|W|$ will not help the network to admit more traffic.

Then, what is the requirement of $|W|$ to admit given upstream traffic? A large number of wavelengths $|W|$ implies a broad tuning range of tunable lasers and requires a large number of receivers at OLT. Both of them will incur high cost. Hence, the number of wavelengths is desired to be as small as possible for low cost. To achieve given upstream traffic rates R, the minimum number of wavelengths $|W|$ is thus $\lceil \sum_i r_i/C \rceil$.

The next question is: to lower the cost, can we further narrow lasers' tuning ranges without decreasing the admissible traffic in the case of using full-range tunable lasers? Equivalently, in the abstracted bipartite subgraph, the problem is to reduce the number of connecting edges between the laser set L and the wavelength set W.

Theorem 1 describes a method of reducing the number of edges without reducing the admissible traffic.

Theorem 1: Given the laser set L and the wavelength set W, if $|L| > |W|$, $(|L|-|W|)|W|+|W|$ is the minimum number of edges needed to admit the same amount of traffic as in the case that all lasers are full-range tunable. In addition, the minimum number of edges is achievable.

Proof: In the case that all lasers are full-range tunable, traffic R is admissible if it satisfies.

$$\begin{cases} r_i \le C & \forall i \\ \sum_{i=1}^{|L|} r_i \le |W|C \end{cases}.$$

Here, we first prove that the minimum number of edges connecting L and W is $(|L|-|W|)|W|+|W|$ to admit the traffic rate R.

For any wavelength w in the wavelength set W, let set U, where $\mathcal{L} \subset L$, contain all the lasers that can be tuned to wavelength w. $|\mathcal{L}|$ is the number of edges connected to one vertex w in the wavelength set W. If $|\mathcal{L}|$ is proved to be no less than $|L|-|W|+1$, then the total number of edges connected to all vertices should be no less than $(|L|-|W|+1)|W|$. The theorem is hence proved.

Assume $|\mathcal{L}|$ is less than $|L|-|W|+1$, say, $|L|-|W|$. That is $|L|-|W|$ lasers are tuned to wavelength w. Then, the remaining $L\backslash\mathcal{L}$ lasers are tuned to wavelengths in $W\backslash\{w\}$ only. Hence, the admissible traffic rate R has to satisfy the condition that $\sum_{l\in L\backslash\mathcal{L}} r_l \le (|W|-1)C$. The admissible traffic is reduced as compared to that in the case that all lasers are full-range tunable. We have therefore proved that the minimum number of edges connecting L and W is $(|L|-|W|)|W|+|W|$ to achieve the same traffic rate R as that achieved in the scenario with all full-range tunable lasers.

We next prove that the minimum number of edges is achievable. One way to achieve it is as follows. Let $|W|$ lasers among all $|L|$ lasers be wavelength-specific lasers, and each of them is respectively tuned to one wavelength in W. The remaining $|L|-|W|$ lasers in W are full-range tunable lasers, i.e., each of them can be tuned to any wavelength in W. The total number of edges in the bipartite graph is $|W|+(|L|-|W|)|W|$, which is the minimum number of wavelengths. Therefore, the admissible traffic is the same as that of the scenario with all full-range tunable lasers. ■

Fig. 3(a) shows one example of using full-range tunable lasers, where any of the five lasers can be tuned to any of the three wavelengths. Fig. 3(b) shows the scheme of reducing the number of full-range tunable lasers. In Fig. 3(b), laser 1 and laser 2 can be tuned to any of the three wavelengths, while laser 3, laser 4, and laser 5 are wavelength-specific lasers tuned to wavelength 1, 2, and 3, respectively. Both of the two cases can accommodate the same admissible traffic rate.

$$\begin{cases} r_i \le C & \forall i \\ \sum_{i=1}^{5} r_i \le 3C. \end{cases}$$

As compared to the case in Fig. 3(a), the configuration as shown in Fig. 3(b), reduces the number of full-range tunable lasers from 5 to 2.

We can draw the following conclusions for the number of lasers $|L|$ and the number of wavelengths $|W|$.

1) $|W| < |L|$; $|L|-|W|$ lasers with full-range tunability and $|W|$ wavelength-specific lasers can admit the largest amount of traffic. This number cannot be further reduced; otherwise, the admissible traffic will decrease.
2) $|W| = |L|$; wavelength-specific lasers can admit the largest traffic, and no tunable lasers are needed. In other words, tunable lasers will not help admit more traffic in this case.

TABLE I
ONE EXAMPLE OF WAVELENGTH CONFIGURATION FOR EIGHT LASERS

wavelength #	1	4	7	8
wavelength-specific lasers #	8	4	7	8
tunable lasers #	0	4	1	0
tuning wavelengths #	1	4	7	1
Admissible traffic rate R	$r_i \le C, \forall i$ $\sum_{i=1}^{8} r_i \le C$	$r_i \le C, \forall i$ $\sum_{i=1}^{8} r_i \le 4C$	$r_i \le C, \forall i$ $\sum_{i=1}^{8} r_i \le 7C$	$r_i \le C, \forall i$ $\sum_{i=1}^{8} r_i \le 8C$

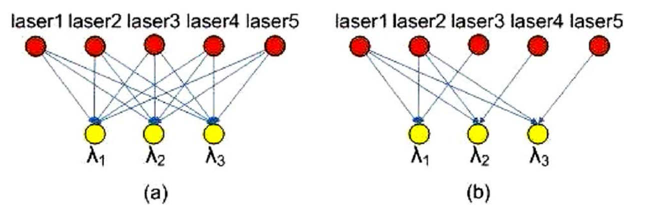

Fig. 3. One example of WDM PON with full-range tunable lasers and wavelength-specific lasers. (a) Full-range tunable lasers and (b) full-range tunable lasers and wavelength-specific lasers.

3) $|W| > |L|$; $|W| - |L|$ wavelengths are always wasted. Increasing the number of wavelengths does not increase the admissible traffic.

Table I shows four scenarios of configuring wavelengths for eight lasers by applying Theorem 1. The scenario of configuring each of eight lasers with one specific wavelength accommodates the largest admissible traffic. The admissible traffic in the scenario of using seven wavelengths is slightly smaller than that of using eight wavelengths. It requires seven wavelength-specific lasers and one full-range tunable laser. The scenario of using one wavelength accommodates the smallest admissible traffic.

IV. DESIGN OF WDM PON WITH LIMITED-RANGE TUNABLE LASERS

The previous section discussed the design of WDM PON with full-range tunable lasers. However, full-range tunable lasers are costly. To lower the laser cost in the network, the alternative schemes are to use relatively cheaper lasers with limited range tunability. Under the condition that limited-range tunable lasers are available, a scheme is needed to select lasers with proper tuning ranges for ONUs.

Assume set $W = \{1, 2, \ldots, |W|\}$ contain all the available wavelengths.

Let sets $L^1, L^2, L^3, \ldots$ be lasers that can be tuned to respective sets of wavelengths of $W^1, W^2, W^3, \ldots$. Then, $W^i \subseteq W, \forall i$; $L^i \cap L^j = \emptyset, \forall i \neq j$; and $\bigcup_i L^i = L$. The problem of determining tuning ranges of lasers is equivalent to mapping L^i to $W^i, \forall i$. We will discuss the problem under the condition that traffic rate R is unknown, and R is known *a priori*, respectively. The main idea is as follows. When R is unknown, we try to let each wavelength be tuned by the same number of lasers for load balancing. When R is known *a priori*, we formulate the problem into a constraint satisfaction problem and then solve it.

Let $\mathcal{N}$ and Δ be the number of a laser's tuning wavelengths and the interval between the laser's tuning wavelengths (channel spacing), respectively. Both $\mathcal{N}$ and Δ can range from 1 to $|W|$.

We assume lasers can stay accurately on their desired wavelengths. Consider two simple cases of $\mathcal{N}$ and Δ.

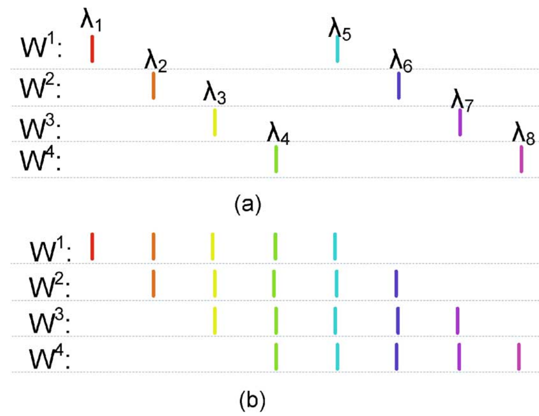

Fig. 4. Tuning ranges of limited-range tunable lasers. (a) $\Delta = 4; W^1 = \{1,5\}; W^2 = \{2,6\}; W^3 = \{3,7\}; W^4 = \{4,8\}$ and (b) $\Delta = 1; W^1 = \{1,2,3,4,5\}; W^2 = \{2,3,4,5,6\}; W^3 = \{3,4,5,6,7\}; W^4 = \{4,5,6,7,8\}$.

1) All lasers have the same Δ, and $\mathcal{N} = |W|/\Delta$. The available lasers can accommodate Δ kinds of tuning ranges. $W^1 = \{1, \Delta+1, 2\Delta+1, 3\Delta+1, \ldots\}, W^2 = \{2, \Delta+2, 2\Delta+2, 3\Delta+2, \ldots\}, \ldots, W^\Delta = \{\Delta, 2\Delta, 3\Delta, \ldots\}$. Fig. 4(a) shows the example with $|W| = 8$ and $\Delta = 4$. $W^1 = \{1,5\}, W^2 = \{2,6\}, W^3 = \{3,7\}$, and $W^4 = \{4,8\}$.
2) All lasers have the same $\mathcal{N}$, and $\Delta = 1$. $W^1 = \{1, 2, \ldots, \mathcal{N}\}, W^2 = \{2, 3, \ldots, \mathcal{N}+1\}, \ldots$ Fig. 4(b) shows the example with $|W| = 8, \mathcal{N} = 5$, and $\Delta = 1$. $W^1 = \{1,2,3,4,5\}, W^2 = \{2,3,4,5,6\}, W^3 = \{3,4,5,6,7\}$, and $W^4 = \{4,5,6,7,8\}$.

Taking the aforementioned two cases of $\mathcal{N}$ and Δ, e.g., we next detail the design process with limited-range tunable lasers. Note that the idea can be applied in solving the problem with any $\mathcal{N}$ and Δ, not just restricted to these two cases.

A. All Lasers Are of the Same Δ, and $\mathcal{N} = |W|/\Delta$

Given Δ, the number of tuning wavelengths of a laser is $|W|/\Delta$. Then, the number of possible tuning ranges of lasers is Δ. $W^1 = \{1, \Delta+1, 2\Delta+1, 3\Delta+1, \ldots\}, W^2 = \{2, \Delta+2, 2\Delta+2, 3\Delta+2, \ldots\}, \ldots$, and $W^\Delta = \{\Delta, 2\Delta, 3\Delta, \ldots\}$. Any two tuning ranges do not have overlapping wavelengths. Wavelengths in set W^i are tuned by lasers in set L^i only. Hence, the upstream traffic rate R is admissible if

$$\begin{cases} r_l \le C & \forall l \\ \sum_{l \in L^i} r_l \le C|W|/\Delta & \forall i \end{cases}.$$

We further discuss the design problem under two cases of the traffic rate R: R is unknown, and R is known *a priori*.

1) R Is Unknown: Under the condition that R is unknown, e.g., the network operator has no idea about the traffic information in an area; we let each wavelength set be tuned by an equal number of lasers for the purpose of load balancing. So, each tuning range with $|W|/\Delta$ wavelengths will be tuned by $|L|/\Delta$ lasers. The interval between tuning wavelengths Δ determines the admissible traffic as follows.

1) If $\Delta = |W|$, then $W^1 = \{1\}, W^2 = \{2\}, \ldots$. All the lasers are wavelength specific. The network accommodates the smallest admissible traffic.
2) If $\Delta = 1$, then $W^1 = \{1, 2, \ldots, |W|\}$. All the lasers are full-range tunable. The network accommodates the largest admissible traffic.
3) If $1 < \Delta < |W|$, the smaller the Δ, the larger the admissible traffic.

2) R Is Known a priori: Given upstream traffic rates R to be admitted, the problem of selecting tuning ranges for lasers can be formulated as follows.

$$\begin{aligned} \text{Given}: &\quad R, W^1, W^2, \ldots, W^\Delta \\ \text{Obtain}: &\quad L^i, \qquad 1 \le i \le \Delta \\ \text{subject to}: &\quad \sum_{l \in L^i} r_l \le C(|W|/\Delta), \qquad 1 \le i \le \Delta \\ &\quad \sum_{l \in L} r_l \le C|W| \\ &\quad L^i \cap L^j = \emptyset \qquad \forall i \ne j \\ &\quad \bigcup_i L^i = L. \end{aligned}$$

If $\sum_{l \in L} r_l = C|W|$, the problem is equivalent to the partition problem, which is NP-complete [18]. Heuristic algorithms can be applied to solve it.

B. $\Delta = 1$

Under the condition that $\Delta = 1$ and each laser can be tuned to $\mathcal{N}$ wavelengths, there are $|W| - \mathcal{N} + 1$ kinds of tuning ranges. $W^1 = \{1, 2, \ldots, \mathcal{N}\}, W^2 = \{2, 3, \ldots, \mathcal{N}+1\}, \ldots$. We discuss the problem under the condition that the traffic rate R to be admitted is unknown and R is known *a priori*, respectively.

1) R Is Unknown: Under the condition that R is unknown, we let $|L|/(|W| - \mathcal{N} + 1)$ lasers, on average, be tuned to $W^i, \forall i$, for load balancing.

Since lasers in L^i are tuned to wavelengths in W^i only, the admissible traffic has to satisfy the following constraint

$$\begin{cases} r_l \le C & \forall l \\ \sum_{l \in L} r_l \le C|W| & \\ \sum_{l \in L^i} r_l \le |W^i| C & \forall i \end{cases}.$$

If $|L^i| > |W^i|$, i.e., $|L|/(|W| - \mathcal{N} + 1) > \mathcal{N}$, the constraint $\sum_{l \in L^i} r_l \le |W^i| C$ is naturally satisfied. The condition for admissible traffic is reduced to

$$\begin{cases} r_l \le C & \forall l \\ \sum_{l \in L} r_l \le C|W| \end{cases}.$$

Fig. 5 shows an example of the aforementioned process. Fig. 5(a) shows that there are three wavelengths and four lasers, and the tuning range $\mathcal{N} = 2$. The lasers' tuning ranges can be either $W^1 = \{\lambda_1, \lambda_2\}$ or $W^2 = \{\lambda_2, \lambda_3\}$, as shown in Fig. 5(b). We let two lasers be tuned to $\{\lambda_1, \lambda_2\}$, and the other two lasers be tuned to $\{\lambda_2, \lambda_3\}$, as shown in Fig. 5(c). For both W^1 and W^2, we have $L^1 = W^1$ and $L^2 = W^2$.

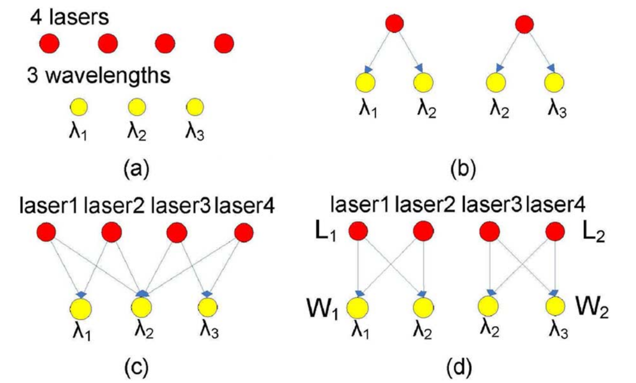

Fig. 5. One example of selecting proper tuning ranges for tunable lasers under the condition that $\Delta = 1$. (a) Lasers and wavelengths, (b) two tuning ranges, (c) select tuning ranges for lasers, and (d) L_1 for W_1, L_2 for W_2.

2) R Is Known a priori: Assume the traffic rate R is known *a priori*. The problem of deciding L^i for each tuning range W^i can be formulated as follows:

$$\begin{aligned} \text{Given}: &\quad \text{traffic rate } R, W^i \\ \text{Obtain}: &\quad L^i, \qquad 1 \le i \le |W| - \mathcal{N} + 1 \\ \text{subject to}: &\quad \sum_{l \in L} r_l \le C|W| \\ &\quad \sum_{l \in L^i} r_l \le C\mathcal{N}, \qquad 1 \le i \le |W| - \mathcal{N} + 1 \\ &\quad \bigcup_{i=1}^{|W|-\mathcal{N}+1} L^i = L \\ &\quad L^i \cap L^j = \emptyset \qquad \forall i \ne j. \end{aligned}$$

When the number of tuning wavelengths $\mathcal{N} = 1$, the lasers are wavelength specific. The problem is equivalent to the partition problem, as discussed in Section IV-A2. When $\mathcal{N} \ge 2$, the problem can be solved by Algorithm 1.

Algorithm 1 Determine L^i for W^i, $\forall i$

```
for i = 1 to |W| − N do
  L^i = ∅
  while Σ_{l∈L^i} R_l > CN do
    Select any element from L, denoted as l*
    if Σ_{l∈L^i} R_l + R_{l*} > CN then
      l* is included into L^i
      l* is deleted from L
    end if
  end while
end for
Include all the remaining elements in L into set L^{|W|−N+1}
```

To determine elements in sets L^i $(1 \le i \le |W| - \mathcal{N})$, Algorithm 1 includes lasers into the set until the constraint $\sum_{l \in L^i} \mathcal{R}_l > C\mathcal{N}$ is violated. Then, the remaining lasers are included into set $L^{|W|-\mathcal{N}+1}$. We shall next prove that Algorithm 1 can solve the problem successfully. For the first $|W| - \mathcal{N}$ sets, $L^1, \ldots, L^{|W|-\mathcal{N}}$, Algorithm 1 guarantees $\sum_{l \in L^i} r_l \leq C\mathcal{N}$. We then show that set $L^{|W|-\mathcal{N}+1}$ also satisfies $\sum_{l \in L^{|W|-\mathcal{N}+1}} r_l \leq C\mathcal{N}$. For the first $|W| - \mathcal{N}$ sets, $\sum_{l \in L^i} r_l > C\mathcal{N} - C$ since $r_l \leq C$. Let $\sum_{l \in L^i} r_l = C\mathcal{N} - C + \epsilon, 0 < \epsilon \leq C$. Then

$$\begin{aligned} \sum_{l \in L^{|W|-\mathcal{N}+1}} r_l &\leq |W|C - (|W| - \mathcal{N})[(\mathcal{N}-1)C + \epsilon] \\ &\leq |W|C - (|W| - \mathcal{N})(\mathcal{N}-1)C \\ &= (|W| - \mathcal{N})(2 - \mathcal{N})C + \mathcal{N}C. \end{aligned}$$

When $\mathcal{N} \geq 2, \sum_{l \in L^{|W|-\mathcal{N}+1}} r_l \leq \mathcal{N}C$. Hence, a solution to the aforementioned algorithm is obtained.

V. Design of WDM PON When the Exact Number of Lasers With Specific Tuning Ranges Is Given

We have considered the scenario in which there are multiple choices of lasers' tuning ranges. In this section, we discuss the scenario in which there are only $|L|$ lasers available, each of which is of a specific tuning range. For example, the network operator already purchased $|L|$ lasers with specific tuning ranges. The problem is how to distribute these given lasers to ONUs.

The solution to this problem will benefit an important WDM PON deployment scenario in which the network operator may want to upgrade the current PON system into another one with larger capacity within a limited budget. Consider the following scenario. Assume the current network is a GPON system with 16 ONUs. Now the network operator wants to replace wavelength-specific lasers at ONUs by wavelength-tunable lasers to increase the system capacity. Assume the network operator has a limited budget to replace only eight lasers. Selecting and upgrading 8 ONUs from the total of 16 ONUs becomes the pressing issue. This problem can be solved by algorithms to be presented next.

We map the problem into a bipartite graph matching problem. Let set O contain ONUs, and set L contain the given lasers with specific tuning ranges. Each ONU in set O is going to be matched to one laser in set L. Note that lasers in L and the wavelength set forms a bipartite graph. Fig. 6(a) shows one example. If the traffic rate is unknown, any matching can be performed. If the traffic rate of ONUs in O is known *a priori*, a good matching between ONUs in O and lasers in L shall be able to make the traffic rate of ONUs in O be admissible.

Denote the bipartite graph formed by lasers in L and wavelengths in W as $\{L \cup W, E_{LW}\}$. The matching should enable rates of ONUs in O be admissible in graph $\{L \cup W, E_{LW}\}$. Let a permutation matrix $\mathbf{P}$ describe the matching between O and L. With matrix $\mathbf{P}$, the traffic rate of lasers in set L is $\mathbf{P}R^O$, where R^O is the traffic rate of ONUs in set O. Given R^O, the matching is to find a permutation matrix $\mathbf{P}$ to ensure that $R = \mathbf{P}R^O$ is the admissible traffic in graph $\{L \cup W, E_{LW}\}$.

Assume L_α and L_β are two subset of L, where $L_\alpha \cup L_\beta = L$. Let the laser sets O_α and O_β be two subsets of O matched to L_α and L_β, respectively. Obviously, $|O_\alpha| = |L_\alpha|$ and $|O_\beta| = |L_\beta|$. Let W_α and W_β be the wavelength sets to which lasers in set L_α and L_β are tuned, respectively. The matching has to ensure the constraint $\sum_{l \in O_\alpha} r_l \leq |W_\alpha|C$ and $\sum_{l \in O_\beta} r_l \leq |W_\beta|C$ be satisfied.

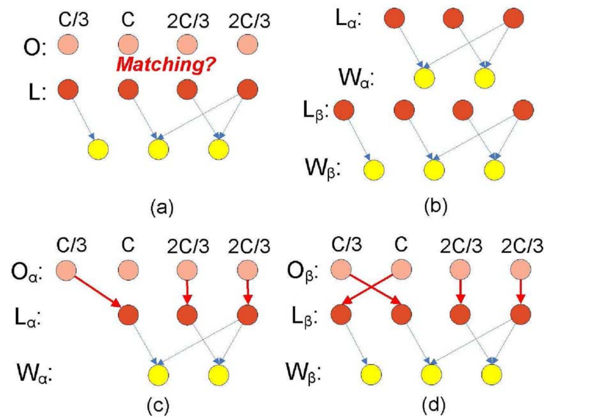

Fig. 6. Assigning lasers to ONUs under the condition that $L_\alpha \subseteq L_\beta$. (a) Rates of *O*, tuning wavelengths of *L*, (b) $L_\alpha \subseteq L_\beta$, (c) decide O_α for L_α, and (d) decide O_β for L_β.

To obtain the matching, there are three cases of $|L_\alpha|, |L_\beta|, |W_\alpha|$, and $|W_\beta|$ to be considered.

1) $|L_\alpha| \leq |W_\alpha|$ and $|L_\beta| \leq |W_\beta|$. Then, $|O_\alpha| \leq |W_\alpha|$ and $|O_\beta| \leq |W_\beta|$. In this case, the constraint $\sum_{l \in O_\alpha} r_l \leq |W_\alpha|C$ and $\sum_{l \in O_\beta} r_l \leq |W_\beta|C$ are naturally satisfied. Therefore, any matching can be applied here.
2) $|L_\alpha| > |W_\alpha|$ or $|L_\beta| > |W_\beta|$. Then, $|O_\alpha| > |W_\alpha|$ or $|O_\beta| > |W_\beta|$. Without losing generality, assume $|L_\alpha| > |W_\alpha|$ and $|L_\beta| \leq |W_\beta|$. The constraint $\sum_{l \in O_\beta} r_l \leq |W_\beta|C$ is naturally satisfied. The matching needs to ensure that the condition $\sum_{l \in O_\alpha} r_l \leq |W_\alpha|C$ is satisfied as well. The strategy is to let O_α contain lasers with small rates, and let O_β contain the remaining lasers.
3) $|L_\alpha| > |W_\alpha|$ and $|L_\beta| > |W_\beta|$. Then, $|O_\alpha| > |W_\alpha|$ and $|O_\beta| > |W_\beta|$. In this case, the matching has to ensure that both constraint $\sum_{l \in O_\alpha} r_l \leq |W_\alpha|C$ and constraint $\sum_{l \in O_\beta} r_l \leq |W_\beta|C$ are satisfied. We further analyze three cases of L_α and L_β: $L_\alpha \subseteq L_\beta$ or $L_\alpha \supseteq L_\beta$, $L_\alpha \cap L_\beta = \emptyset$, and $L_\alpha \cap L_\beta \neq \emptyset$.

Next, we analyze three cases of L_α and L_β under the condition of $|L_\alpha| > |W_\alpha|$ and $|L_\beta| > |W_\beta|$ in detail.

A. $L_\alpha \subseteq L_\beta$ or $L_\alpha \supseteq L_\beta$

Sine $L_\alpha \subseteq L_\beta$ or $L_\alpha \supseteq L_\beta, O_\alpha \subseteq O_\beta$ or $O_\alpha \supseteq O_\beta$. Assume $L_\alpha \subseteq L_\beta$, then $L_\beta = L$. $\sum_{l \in O_\beta} r_l \leq |W_\beta|C$ is satisfied. The matching has to ensure $\sum_{l \in O_\alpha} r_l \leq |W_\alpha|C$. The strategy is to let set O_α contain lasers with small rates, and let set O_β contain lasers with large rates.

Fig. 6 shows one example of the matching process. Fig. 6(a) shows O, L, and W. Fig. 6(b) shows L_α and L_β as well as their connected wavelengths. In this specific example, $L_\alpha \subseteq L_\beta$. In Fig. 6(c), lasers with small rates are included into set O_α. Fig. 6(d) shows the final matching between O and L.

B. $L_\alpha \cap L_\beta = \emptyset$

Then, $O_\alpha \cap O_\beta = \emptyset$. The matching problem is equivalent to the problem of partitioning O into two nonoverlapping sets O_α and O_β, where $\sum_{l \in O_\alpha} r_l \leq |W_\alpha|C$ and $\sum_{l \in O_\beta} r_l \leq |W_\beta|C$. This partition problem is NP-complete. Heuristic algorithms can be employed to solve it.

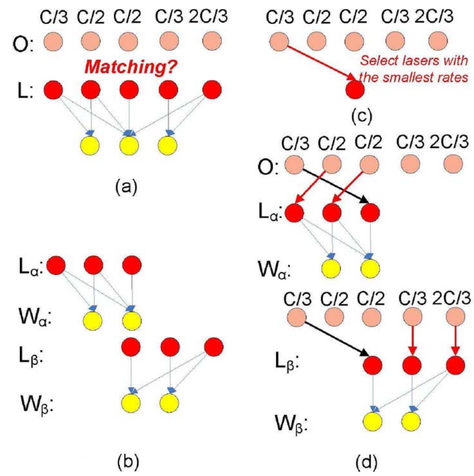

Fig. 7. Assigning lasers to ONUs under the condition that $L_\alpha \cap L_\beta \neq \emptyset$. (a) Rates of O, tuning wavelengths of L, (b) $L_\alpha \cap L_\beta \neq \emptyset$, (c) decide Θ, (d) partition $L \setminus \Theta$ into $L_\alpha \setminus \Theta$ and $L_\beta \setminus \Theta$.

C. $L_\alpha \cap L_\beta \neq \emptyset$

Then, $O_\alpha \cap O_\beta \neq \emptyset$. Let $\Theta = O_\alpha \cap O_\beta$. Then, the matching has to guarantee.

$$\begin{cases} \sum_{l\in O_\alpha} r_l \leq C|W_\alpha| \\ \sum_{l\in O_\beta} r_l \leq C|W_\beta| \end{cases}$$
$$\Rightarrow \sum_{l\in O_\alpha} r_l + \sum_{l\in O_\beta} r_l \leq C(|W_\alpha| + |W_\beta|)$$
$$\Rightarrow \sum_{l\in \Theta} r_l \leq C(|W_\alpha| + |W_\beta|) - \sum_{l\in L} r_l.$$

To satisfy the aforementioned constraint, we include lasers with the smallest rates into set Θ. The remaining problem is to partition L/Θ into L_α/Θ and L_β/Θ. The partition has to guarantee that $L_\alpha/\Theta \cap L_\beta/\Theta = \emptyset, \sum_{l\in L_\alpha/\Theta} r_l \leq (C|W_\alpha| - \sum_{l\in\Theta} r_l)$, and $\sum_{l\in L_\beta/\Theta} r_l \leq (C|W_\beta| - \sum_{l\in\Theta} r_l)$. Hence, the remaining problem is reduced to the problem discussed in Section V-B. It is NP-complete.

Fig. 7 shows one example of the matching process. Fig. 7(a) shows O, L, and W. Fig. 7(b) shows L_α and L_β, where $L_\alpha \cap L_\beta \neq \emptyset$. In Fig. 7(c), the laser with the smallest rates is included into Θ. Fig. 7(d) shows the partition of L/Θ into two nonoverlapping sets L_α/Θ and L_β/Θ.

This shows the strategies of partitioning the laser set O into two subsets, which are assigned to two subsets of L, respectively. The matching between O and L can be obtained by recursively performing the process for any two subsets of L. However, the number of subsets of L exponentially increases with the size of $|L|$. It is not practical to go through every two subsets of L. From the aforementioned discussion, we know that satisfying rate constraints of lasers in some laser sets is the key to addressing the matching problem. These laser subsets are those with the number of lasers being greater than the number of wavelengths to which the lasers can be tuned, i.e., subset L_α with $|L_\alpha| > |W_\alpha|$. Algorithm 2 presents the matching scheme between O and L.

Algorithm 2 Matching between O and L

Determine all the subsets L_α with $L_\alpha \subset L$ and $|L_\alpha| > |W_\alpha|$, including these subsets in set $\mathbb{L}$
Sort L_α in the descending order of its size.
for each $L_\alpha \in \mathbb{L}$ **do**
  if $\exists L_{\alpha'} \in \mathbb{L}$ and $L_{\alpha'} \not\subseteq L_\alpha$ **then**
    Determine O_α and $O_{\alpha'}$ which are matched to L_α and $L_{\alpha'}$, respectively
  else
    Determine O_α which is matched to L_α.
  end if
  Eliminate O_α from $\mathbb{L}$
end for

In Algorithm 2, we first determine all the subsets L_α with $|L_\alpha| > |W_\alpha|$ and then sort these subsets in the descending order of their sizes. The subsets with large sizes are matched first. For any subset L_α, if there exists another subset $L_{\alpha'}$ with $L_{\alpha'} > |W_{\alpha'}|$ and $L_{\alpha'} \not\subseteq L_\alpha$, we partition $O_{\alpha'} \cup O_\alpha$ into $O_{\alpha'}$ and O_α to match L_α and $L_{\alpha'}$, respectively, by using methods described in Sections V-A and V-B. Otherwise, we place the lasers with small rates into O_α to match L_α by applying the method described in Section V-C. Then, the matching between O and L is completed by performing this procedure for every L_α with $|L_\alpha| > |W_\alpha|$.

VI. Conclusion

We consider WDM PONs with ONUs being equipped with tunable lasers for upstream data transmission. Lasers with broader tuning ranges yield more admissible traffic, but require sophisticate technology, which implies high cost. To achieve the optimal tradeoff between the tuning ranges of laser and the admissible traffic of the network, we have investigated the problem of admitting the maximum traffic or given traffic by using lasers with tuning ranges as narrow as possible. Three scenarios have been specifically analyzed: 1) full-range tunable lasers and wavelength-specific lasers are available; 2) limited-range tunable lasers are available; and 3) the exact number of lasers with specific tuning ranges are given. In Scenario 1), we replace some full-range tunable lasers with wavelength-specific lasers without decreasing the admissible traffic. In Scenario 2), we select lasers with proper tuning ranges to maximize the admissible traffic. In Scenario 3), we allocate lasers to ONUs so that the given rate can be admitted. The provided guidelines in each scenario can maximize the admissible traffic, decrease the tuning ranges of lasers and hence reduce the capital investment of the system.

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