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Bin-Packing-Based Online Dynamic Bandwidth and Wavelength Allocation Algorithm in Super-PON

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ABSTRACT Super passive optical network (Super-PON) is a next-generation Ethernet PON (NG-EPON) candidate that is envisaged to provide high data rate and low latency. For NG-EPON, there are two types of algorithms that manages bandwidth and wavelength scheduling, namely offline and online. The latter method is more scalable and efficient than the former method. Several online algorithms exist that propose schemes to manage wavelength and bandwidth scheduling. However, these algorithms lack in efficient wavelength utilization and switching. In this work, we propose a novel online bin-packing based dynamic bandwidth and wavelength allocation (DBWA) algorithm for Super-PON, namely updated best fit bin-packing (UBF-BP). This algorithm limits the wavelength switching per cycle, and uses the modified version of best fit bin-packing (BF-BP) technique for optimal wavelength allocation. Simulation results show that the proposed DBWA algorithm has a low complexity and overcomes the inefficiencies of wavelength utilization and switching. This results in lower network delay and higher channel utilization than the state-of-the-art DBWA. Furthermore, to verify the correctness of the proposed algorithm, we propose an analytical model and validate these simulation results with the analytical results.

INDEX TERMS Bin-packing, DBWA, delay analysis, NG-EPON, online algorithm, super-PON.

I. INTRODUCTION

With the increase in the subscribers of high definition multi-media applications, mobile backhauling and content-rich cloud services, the access network data rate requirement is increasing exponentially [1]. To cope with this requirement, passive optical networks (PONs) are becoming prominent solution owing to their high capacity and economical nature [2], [3]. IEEE 802.3ca is developing PON technologies that can fulfill future PON applications. These technologies are known as next-generation Ethernet PON (NG-EPON) [4]. NG-EPON is envisaged to operate at the high data rates (minimum 10 Gbps), long network reach (20-100 km), large split ratios (64-1024), and multiple wavelengths within the same PON [5]. As Super-PON is able to provide all these envisaged promises, it is seen as the prominent NG-EPON proposal [6], [7]. Additionally, Super-PON provides backward compatibility with the legacy PONs, i.e., it is capable of coexisting with the already existing optical distribution networks (ODN) [8]. This capability makes Super-PON an economical solution.

In Super-PON, to allocate the transmission slot and wavelength to an optical network unit (ONU), the optical line terminal (OLT) transmits a control message called GATE. Immediately after receiving the GATE message, the ONU starts transmitting its Ethernet data packets that are followed by a REPORT message. The REPORT message states the current buffer occupancy. The use of guard band between the GATE transmission for two consecutive ONUs prevents data overlapping. Furthermore, in Super-PON there are multiple wavelengths, and a group of ONUs dynamically share each wavelength. How these ONUs are grouped impacts network performance. Furthermore, in the downstream direction (i.e., from the OLT to ONUs), the OLT broadcasts the data making it a collision-free transmission. However, in the upstream direction (i.e., from the ONUs to OLT), the

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ONUs share the resources in a statistically multiplexed manner making this transmission control more strenuous than the downstream direction. Additionally, in a multi-wavelength network, overutilization of a few wavelengths leads to larger latency while underutilization results in an unbalanced use of bandwidth [9]. Hence, it is significant to present a vigorous scheme that effectively deals with bandwidth and wavelength management.

The upstream bandwidth scheduling and wavelength assignment algorithms are broadly of two types: offline and online. In an offline algorithm, the OLT makes wavelength assignment (and sometimes bandwidth scheduling) decision after receiving the REPORT messages from all ONUs [10], [11]. In an online algorithm, the OLT makes both decisions (i.e., the decision of wavelength assignment and bandwidth scheduling) jointly immediately after receiving and processing the REPORT message from an ONU [12]. Although, considering the global REPORT messages in an offline algorithm helps in taking fair scheduling decisions and reduces the algorithm complexity, but the online algorithms are efficient, scalable and have lower frame queuing delay [12], [13].

Many online dynamic bandwidth and wavelength allocation (DBWA) algorithms are already available in the literature that present strategies to manage both wavelength and bandwidth in NG-EPON [12]–[20]. In [12], the authors propose early finish time (EFT) and latest finish time (LFT) that use the first available wavelength and latest finish time wavelength respectively, for scheduling. The authors in [13] propose a joint wavelength and time allocation algorithm that uses an optimal switching of wavelengths with EFT. The authors of [14] and [15] propose the use of a just-in-time scheme along with Bayesian estimation and prediction based bandwidth allocation. The authors of [16] employ an algorithm that uses void filling in combination with EFT and multi-thread polling. In [17], the authors suggest the minimization of the number of voids that form due to scheduling considering delay constraints. In [18], the authors propose the first-fit DBWA algorithm where to obtain zero resequencing delay, the earliest available wavelength channel is given to an ONU. The authors in [19] propose an algorithm that employs a genre of the online next-fit DBWA algorithm and optimizes the wavelength and bandwidth scheduling according to the prerequisite delay obligations of the operator. In [20], the authors present an adaptive satisfaction with inclination (ASWI) DBWA algorithm that uses an inclination coefficient which adjusts according to the changing network load and provides differentiated service. However, these algorithms suffer from complex predictions, longer delays, inefficient wavelength utilization and switching, and resource limitations (like a small number of users, small reach, etc.).

In this work, we propose a novel DBWA algorithm that uses the updated best fit bin-packing (UBF-BP) technique for allocating wavelengths dynamically. The best fit bin-packing (BF-BP) technique is widely used to pack the objects of different sizes into a finite number of containers or bins [21]. In Super-PON, we use the updated version of this technique to pack the ONUs demanding different size transmission slots into a finite number of wavelengths. Furthermore, our DBWA algorithm is an online algorithm (i.e., joint allocation of wavelength and bandwidth).

The critical contributions of the proposed UBF-BP algorithm are as follows:

1) To improve the wavelength utilization efficiency, we propose the use of BF-BP based wavelength allocation. The BF-BP algorithm suggests the optimal wavelength that suits best to the ONU based on its REPORT message.
2) To limit the network delay that increases due to free wavelength switching, we impose the condition of optimal wavelength switching [13]. This condition restricts the number of times an ONU can switch in a cycle. This restriction, in turn, reduces the tuning components guard time resulting in reduced network delay.
3) To further reduce the wavelength switching, we consider the available space on the current wavelength of an ONU. If this space on current wavelength can accommodate the ONU again, then there is no wavelength change.
4) For fair bandwidth allocation, we use the limited surplus (LS) grant sizing scheme. This scheme not only restricts the maximum grant to an ONU but also provides a surplus grant in the case of large bandwidth requirements.
5) To validate the performance of the UBF-BP algorithm, we also propose an analytical delay model for it.

The structure of the rest of the paper is as follows. Section II introduces Super-PON architecture that we consider for this algorithm. In Section III, we present the proposed online DBWA algorithm in detail. Next, in Section IV, we discuss an analytical delay analysis of the proposed algorithm. Section V covers the incisive discussion on the simulation and theoretical results, followed by the complexity analysis of the proposed algorithm. Finally, we present the concluding remarks in Section VI.

II. SUPER-PON

The baseline stacked architecture of Super-PON system that we contemplate for the proposed DWBA algorithm that is IEEE MAC (media access control) compliant is shown in Fig. 1. The architecture employs four pairs of wavelengths for the upstream and downstream communication. This architecture is in a tree topology, with the central office (CO) forming the root and the customer premises forming the leaves. The root and the leaves are linked using an optical distribution network (ODN).

This architecture is formed by stacking four 10G-EPONs (10 Gigabit EPONs) using wavelength division multiplexing (WDM). This stacking helps in increasing the split ratio in a scenario where a single operator is present [22]. Additionally, it can be used for unbundling in a scenario where only one wavelength is given per operator [23]. In this manner,

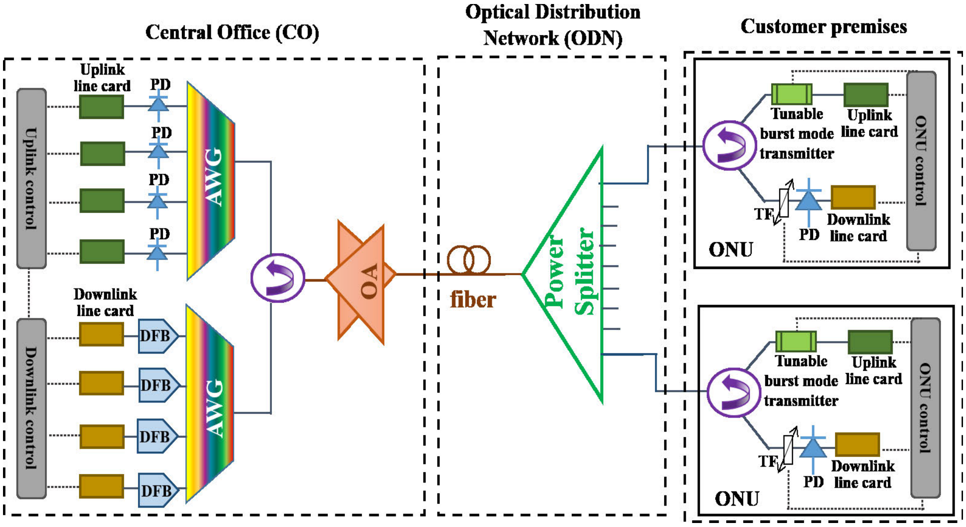

FIGURE 1. Super-PON architecture (Abbreviations in figure: PD - Photodiodes, AWG - Arrayed waveguide grating, DFB - Distributed feedback laser, OA - Optical amplifiers, TF - Tunable optical filter).

stacking of 10G-EPONs not only induces the flexibility but also allows statistical distribution of available spectrum. Moreover, this architecture also reuses the power splitter based legacy architectures that results in the backward compatibility and curtails the construction cost [24].

At the CO end, we use distributed feedback (DFB) lasers to generate required wavelengths that are acting as the downstream data sources. We use DFB lasers because they are part of NG-EPON standard [25], and unlike vertical-cavity-surface-emitting lasers (VCSELs), they do not have reach limitations [26]. These lasers are multiplexed using WDM. Furthermore, for boosting the power budget and pre-amplifying the upstream signals, we use optical amplifier. The communication between the CO and customer premises is through ODN. The optical fiber and power splitter form this ODN. The power splitter broadcasts everything that it receives from any of the connecting ends. Thus, the ONU in this Super-PON architecture employs a tunable burst-mode transmitter and a tunable receiver. The use of a tunable filter helps to tune in any of the pre-decided wavelengths. Furthermore, in Table 1, we summarize the relevant notations that we consider in this paper.

TABLE 1. Notations used in the paper.

Notation	Description
N_{sc}	Number of switching per cycle
T_o	Transmission overheads
N_w	Number of available wavelengths
T_c	Cycle time
T_{max}	Maximum cycle time
T_T	Tuning time
N_o	Number of ONUs
T_i	Time at which the OLT receives i^{th} REPORT message
T_{NT}	Non-transition period
L_R	Line rate per wavelength
D_j	Data bits requested by j^{th} ONU
S_i	Maximum space on a wavelength (in bits)
N_a	Average number of ONUs per wavelength
ρ_n	Network load
P_{on}	Probability of an ONU to be ON
R_{on}	Maximum data rate of an ONU
N_{on}	Number of active ONUs
B	Maximum buffer size at the ONU
T_g	Guard band
Δ	RTT between the OLT and the ONU
P_s	Switching probability
F_I	Fairness index

III. PROPOSED DBWA ALGORITHM FOR SUPER-PON

The statistically uncertain traffic profile obligates the use of an online transmission scheduling algorithm at the OLT. The main objectives for designing an online algorithm are: low network delay, high channel utilization, and low packet loss rate. These objectives should also support the large number of users (64-1024) and long network reach (20-100 km). To fulfill these objectives, we propose an online DBWA algorithm for Super-PON, named UBF-BP. The idea is to take the ONU's REPORT message as an input and apply the modified (or updated) BF-BP algorithm for wavelength allocation, and simultaneous and interleaved polling with adaptive cycle time (SIPACT) for bandwidth scheduling.

A. BEST FIT BIN-PACKING

Bin-packing is an NP-hard optimization problem (the same as wavelength allocation in Super-PON), which packs certain finite items of a list into the distinct regions called bins in such a manner that bins are efficiently utilized. As it is difficult to find the exact solution for the NP-hard problem, the research on bin-packing is mainly focusing on the performance of heuristics. One such solution is the *best fit* bin-packing (BF-BP).

In the BF-BP algorithm, an item is placed in a partially filled bin that is large enough to accommodate it and has the smallest residual capacity. If there is no such bin that satisfies this condition then a new bin is formed and the item is placed in that new bin [27]. The best fit algorithm keeps the list of current bins sequenced according to their size, and an item is placed in the current fullest bin that fits it [28]. In Super-PON, we propose the use of this algorithm to pack the ONUs (or items) into the finite number of wavelengths (or bins) efficiently. In this manner, the use of the BF-BP algorithm in Super-PON improves its wavelength utilization efficiency. However, our version of the BF-BP algorithm differs from the original BF-BP algorithm in two ways. First, in our case, the number of wavelengths is limited, while in the original version, there are unlimited bins. Second, in our case, an ONU can switch to another wavelength, while in the original version, an item stays in the assigned bin forever.

B. THE UBF-BP ALGORITHM

The OLT uses our version of the BF-BP algorithm to assign a wavelength to the ONU. This wavelength is either the same as the current wavelength on which the ONU is or a new wavelength. If it is a new wavelength, then the ONU takes some time to tune (or switch) to this new wavelength. This time is known as tuning time (denoted as T_T, varies from 100 μs to 2 ms depending upon the laser), and this time adds up as the switching delay in the network. Therefore, unrestricted wavelength switching results in large network delay. In the BF-BP algorithm, there is no provision to limit the wavelength switching. So, we update this algorithm by limiting this switching and rename it as the UBF-BP algorithm. We provide these limiting constraints below.

1) CONSTRAINTS ON WAVELENGTH SWITCHING

We impose this limitation in two ways. We first check for optimal switching condition and if this condition is fulfilled, then we check the available space on the current wavelength. Both these conditions are discussed as follows:

- *Optimal switching*: As stated earlier, unlimited wavelength switching increases the network delay. To restrict the wavelength switching, we calculate the optimal number for which an ONU can switch to a new wavelength per cycle. This switching number (N_{sc}) is given as [13]

$$N_{sc} \leq T_o N_w \times \left(\frac{T_{max} - T_c}{T_c T_T}\right) \tag{1}$$

where T_o denotes the overheads due to guard band and control messages (i.e., REPORT and GATE), N_w is the number of available wavelengths, T_{max} is the maximum cycle time, and T_c denotes the cycle time, i.e., the time difference between two consecutive GATE messages to an ONU. An ONU switches to a new wavelength only if the following condition is fulfilled [13]

$$T_{NT} > N_o T_c / N_{sc} \tag{2}$$

where T_{NT} denotes the time epoch of an ONU on the same wavelength (i.e., non-transition period), and N_o denotes the number of active ONUs. If this condition for limiting the wavelength switching is true, then we check the second condition, i.e., the available space on the current wavelength.

- *Available space on the current wavelength*: The OLT knows the current wavelength on which the ONU is. Taking advantage of this knowledge, it checks the current available space on this wavelength. In our case, the space (in bits) on w^{th} wavelength for i^{th} REPORT message ($S_{w,i}$) is given as

$$S_{w,i} = \begin{cases} S_{w,i-1} + ((T_i - T_{i-1})L_R) - D_j, & \text{if NSC} \\ S_{w,i-1} + ((T_i - T_{i-1})L_R), & \text{else} \end{cases} \tag{3}$$

where L_R is the line rate of a wavelength, T_i is the time at which the OLT receives i^{th} REPORT message, D_j is the data bits requested by j^{th} ONU, and NSC denotes the non-switching case, i.e., the case where the ONU retains the same wavelength. This available space changes with each REPORT message. It also changes because multiple ONUs share a single wavelength and request different bandwidths. Furthermore, the maximum space (in bits) on a wavelength when the OLT receives i^{th} REPORT message is given as

$$S_i = L_R \times T_i \tag{4}$$

In order to restrict the size of the array storing S_i, we reset S_i to zero with every registration cycle (a periodical process where the OLT registers and locate the active ONUs). Now, if the current available space on the wavelength can handle the current bandwidth request of the ONU, then we do not apply the BF-BP algorithm and assign the same wavelength again to the ONU. Assuming that w is the current wavelength of j^{th} ONU, we introduce the following condition for this

$$(S_{w,i} \geq D_j) \quad \text{and} \quad (S_{w,i} - D_j < 2S_i) \tag{5}$$

Using (5), we check two conditions. First, we check whether the space (in bits) on the current wavelength w can accommodate the ONU's request or not. Second, we check that after accommodating the ONU's request, the residual space on w^{th} wavelength is less than the maximum residual space or not (given by $2S_i$). This condition ensures that the wavelength has the minimum residual space after accommodating the ONU.

2) WAVELENGTH SCHEDULING IN THE UBF-BP ALGORITHM

In this manner, we reduce the wavelength switching, which results in a low network delay. Incorporating all the above restrictions, Algorithm 1 summarizes the proposed UBF-BP algorithm. Every time a REPORT message comes from an ONU, the OLT performs the wavelength allocation using this Algorithm 1 in the following manner:

- Assuming w as the current wavelength of the ONU, we first initialize the space (in bits) on w^{th} wavelength ($S_{w,i}$), the residual space (in bits) left on a wavelength (m_s), and the index of the best suitable wavelength (b) (in line 1).

- In line 2, we check whether the ONU can (or cannot) switch to a new wavelength according to the optimal switching condition (given by (2)).
- Line 3 works if the condition in line 2 is true. In line 3, we check whether the current space (in bits) on the current wavelength of the ONU can (or cannot) accommodate it again (given by (5)).
- Line 4 and 5 works if the condition in line 3 is true. This means that the current space on the current wavelength can accommodate the ONU. Hence, in line 4, we retain the current wavelength (w) of the ONU and update the space (in bits) on this wavelength in line 5.
- Line 6 to 15 works if the condition given by line 3 is false. In this part of the algorithm, we apply the BF-BP algorithm to find the best suitable wavelength. In line 8, we check whether the current space (in bits) on k^{th} wavelength is large enough to support the data bits requirement of j^{th} ONU. The value of k varies from 1 to the value of N_w (see line 7). If this condition is true for any k^{th} wavelength, then k^{th} wavelength is the best suitable wavelength (and is stored in variable b) for j^{th} ONU (see line 9). Further, we update the residual space (in bits) left (m_s) for every wavelength fulfilling the condition (in line 10). In this manner, the output of the BF-BP algorithm gives the wavelength (stored in variable b) with the lowest residual space (ensured using m_s) after accommodating j^{th} ONU.
- In line 13, we check whether the minimum space (in bits) left (m_s) is less than its initial value (given in line 1). If this condition is true, then it means that condition given in line 8 is true for at least one of the wavelengths (that is stored in variable b). So, we assign b^{th} wavelength to j^{th} ONU (in line 14) and update its available space (in bits) in line 15.
- Line 16 to 19 works if the conditions in line 13 is false. This means that none of the wavelengths can fulfill the data bits requirement of j^{th} ONU. Hence, the BF-BP algorithm is unable to provide any wavelength to this ONU. In this case, we find the wavelength with the maximum available space (we denote this wavelength by m) and place the ONU on this wavelength (see line 18). We then update the space (in bits) on this wavelength in line 19.
- Line 22 to 24 works if the condition in line 2 (optimal switching condition) is false. This means that the time for which the ONU is on the current wavelength is less than the optimal switching time. Hence, we retain the current wavelength w of the ONU (see line 23) and update its available space (in bits) in line 24.

For further understanding of the proposed algorithm, we represent it in the form of a flowchart (see Fig. 2). Assume that in a Super-PON the OLT receives a REPORT message from j^{th} ONU. It first initializes $S_{w,i}$, b, k, and m_s. After that, the OLT executes the UBF-BP algorithm for wavelength allocation. For easy understanding, we divide the algorithm in three cases (see Fig. 2).

Algorithm 1 Online Updated Best Fit Bin-Packing (UBF-BP)

```
1. Initialize $S_{w,i} = S_{w,i-1} + (L_R \times (T_i - T_{i-1}))$, $m_s = 2S_i$, and $b = 0$
2. If ($T_{NT} > N_o T_c / N_{sc}$)
3.     If [($S_{w,i} \geq D_j$) And ($S_{w,i} - D_j < m_s$)]
4.         Then place $j^{th}$ ONU on $w^{th}$ wavelength
5.         And $S_{w,i} = S_{w,i} - D_j$
6.     Else
7.         For $k = 1$ to $N_w$
8.             If ($S_{k,i} \geq D_j$) And ($S_{k,i} - D_j < m_s$)
9.                 Then $b = k$
10.                And $m_s = S_{k,i} - D_j$
11.            EndIf
12.        End
13.        If ($m_s < S_i$)
14.            Then place $j^{th}$ ONU on $b^{th}$ wavelength
15.            And $S_{b,i} = S_{b,i} - D_j$
16.        Else
17.            $m = \underset{m}{argmax}\, S_{m,i}$
18.            Place $j^{th}$ ONU on $m^{th}$ wavelength
19.            And $S_{m,i} = S_{m,i} - D_j$
20.        EndIf
21.    EndIf
22. Else
23.    Retain current wavelength $w$
24.    And $S_{w,i} = S_{w,i} - D_j$
25. EndIf
```

Case 1: We begin by checking the first condition for restricting the wavelength switching, i.e., the optimal switching criteria given by (2). If this condition is false, then case 2 and 3 do not execute, and we retain the current wavelength. However, if this condition is true, then the algorithm moves to case 2.

Case 2: In this case, we check the second condition for restricting wavelength switching given by (5). If this condition is true, then case 3 does not execute. It means that the current wavelength can accommodate the ONU again, and hence, we retain the current wavelength of the ONU. However, if this condition is false, then the algorithm moves to case 3.

Case 3: In this case, we execute the BF-BP algorithm to find the best suitable wavelength for the ONU according to its bandwidth requirement. The BF-BP algorithm searches through all the available active wavelengths and selects the wavelength with the smallest residual space (in bits) left after accommodating the ONU (stored in variable b). If such a wavelength is found, then we assign that wavelength (b) to the ONU. If we do not find such wavelength, then the OLT selects the wavelength with the maximum available space (denoted by m, in bits) and assign that wavelength to the ONU.

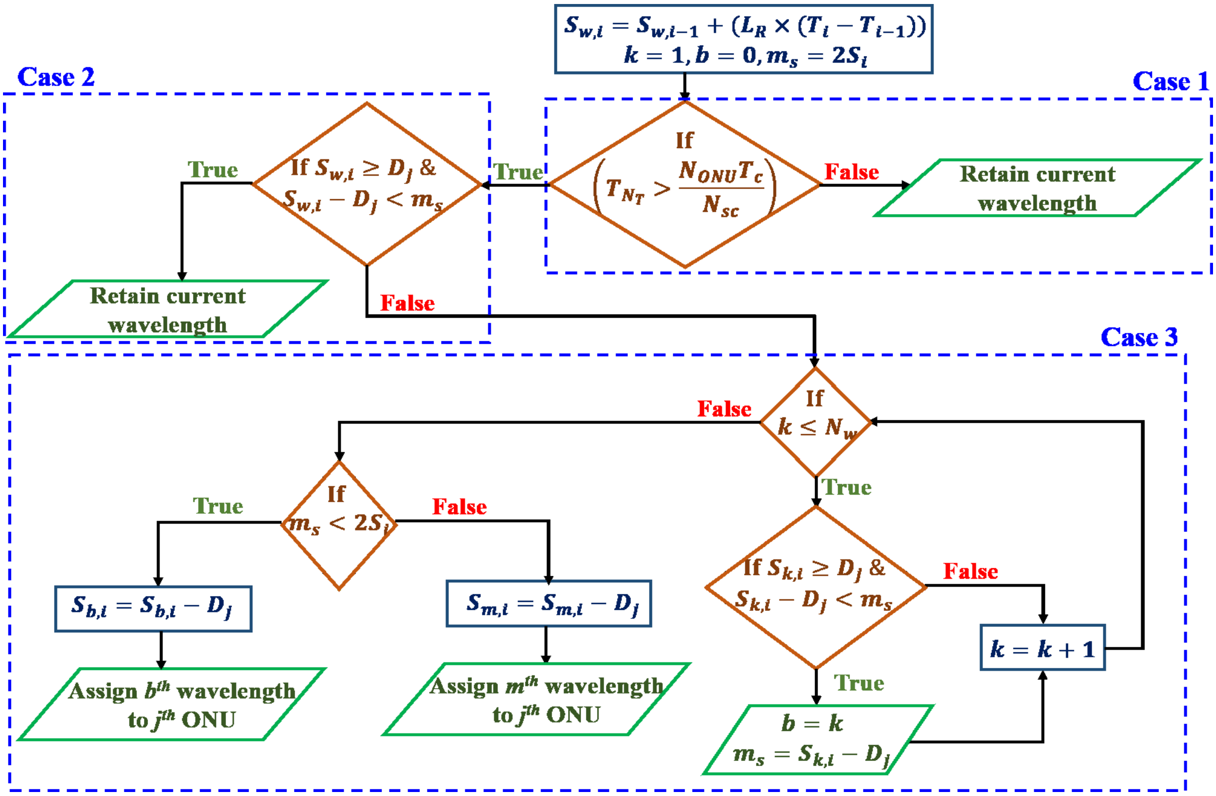

FIGURE 2. Flowchart of the proposed UBF-BP algorithm (*w* is the current wavelength of the ONU, and *m* is the wavelength with the maximum available capacity).

3) BANDWIDTH SCHEDULING IN THE UBF-BP ALGORITHM

In this manner, we propose the use of the UBF-BP algorithm for wavelength allocation at the OLT. Furthermore, for bandwidth scheduling, we use SIPACT [29] at the OLT. In Fig. 3, we show a typical SIPACT algorithm timing diagram. In this figure, we assume four wavelengths (represented as λ_1, λ_2, λ_3, and λ_4) and j^{th} ONU. The OLT transmits a GATE message frame containing the allocated wavelength and transmission slot (or grant size) to j^{th} ONU. As soon as the ONU receives this message, it starts transmitting its packets on the allocated wavelength considering the allocated transmission slot size. At the end of every transmission slot, the ONU transmits a REPORT message that conveys its current buffer state. In the next cycle, the OLT grants the transmission slot according to this REPORT message.

C. GRANT SIZING SCHEMES

At the OLT, we obtain the size of the transmission slot using one of the two grant sizing schemes, namely LS and gated. These schemes are as discussed below.

a) *LS grant sizing scheme*: The motivation behind this scheme is to induce fairness in bandwidth allocation. In the limited grant sizing scheme, the OLT decides the ONU's transmission slot (or grant, G_u) considering the upstream traffic only. The grant G_u (in bits), in this case, is given as

$$G_u = \mathrm{Min}(D_j, S_{max}) \tag{6}$$

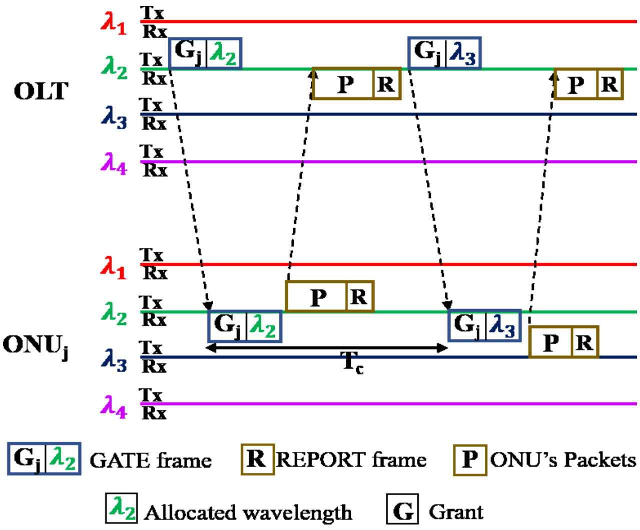

FIGURE 3. SIPACT algorithm timing diagram.

where Min() gives the minimum of the quantities within braces, and S_{max} is the maximum transmission slot per cycle (in bits). S_{max} is calculated as

$$S_{max} = \frac{T_{max} \times N_w \times L_R}{N_o} \tag{7}$$

Nevertheless, in the LS grant sizing scheme if the requested transmission slot by an ONU is less than the maximum transmission slot, then the OLT keeps a surplus transmission slot for that ONU. This surplus transmission slot (S_+) is calculated as

$$S_+ = S_{max} - D_j \tag{8}$$

Now, whenever this ONU requests a larger D_j ($> S_{max}$) due to bursty traffic, then the OLT grants this S_+ in addition to S_{max}. Grant G (in bits), in this case, is given as

$$G = S_{max} + S_+ \tag{9}$$

b) *Gated grant sizing scheme*: In this scheme, the OLT does not restrict the transmission slot of any ONU. The OLT grants the transmission slot the same as the slot requested by the ONU. Hence, grant G (in bits), in this case, is given as

$$G = D_j \tag{10}$$

In both the grant sizing schemes, the decision of transmission slot size is dependent only on the upstream direction traffic, i.e., we neglect the downstream direction traffic for this decision. This is because in the upstream direction, ONUs share the resources while the downstream direction traffic is collision free.

IV. DELAY ANALYSIS CONSIDERING PARETO DISTRIBUTED SOURCES

In this section, we present a model that analyses the delay behavior of the proposed algorithm. Additionally, to recreate Internet traffic behavior, we use Pareto distributed bursty sources [30], [31]. In these sources, there is a burst of packets in the ON period (T_{on}). This ON period is trailed by an OFF period (T_{off}) where there is no packet generation. The probability distribution function for Pareto distribution is given as

$$P(x) = \frac{\alpha\beta^{\alpha}}{x^{\alpha+1}} \qquad x \geq \beta \tag{11}$$

where α is the shape parameter, and β is the location parameter and is taken as the minimum value of x. T_{on} and T_{off} periods of Pareto distributed sources are characterized by distinct values of α and β denoted as α_{on}, β_{on} and α_{off}, β_{off}, respectively.

A. DELAY MODEL FOR THE UBF-BP ALGORITHM

For this modeling, we first assume that N_a denotes the average number of ONUs per wavelength and is given as

$$N_a = \frac{N_o}{N_w} \tag{12}$$

Furthermore, we also consider that ρ_n denotes the network load[1] generated by the Pareto distributed traffic and is calculated as

$$\rho_n = \frac{P_{on}N_oR_{on}}{N_wL_R} = \frac{N_{on}R_{on}}{L_R} \tag{13}$$

where P_{on} is the probability of an ONU to be ON, R_{on} is the maximum data rate (in bits/sec) of an ONU, and N_{on} is the number of active ONUs. Now, using (4), (13) can be updated in the following manner.

$$\rho_n = \frac{P_{on}N_oR_{on}T_i}{N_wS_i} = \frac{N_{on}R_{on}T_i}{S_i} \tag{14}$$

We begin the analysis by first considering the non-switching case, i.e., the case where the ONU remains on the same wavelength as the previous cycle. In this case, at a low network load, the cycle length is mainly governed by the reach (defined by the round trip time (RTT)) of the PON. However, at a high network load, the cycle length is dependent on the network load. Hence, the average cycle length for the non-switching case is calculated as the average of the maximum of both low and high network load cases. However, at very high network load, the maximum buffer size (B) at the ONU limits the average cycle length. Therefore, the average cycle length (T_{cn}) is given as [30]

$$T_{cn} = E\left[Max\left(Min\left(Max\left(\frac{N_aT_g}{1-\rho_n}, \Delta\right), \left\lceil \frac{S_i}{T_iR_{on}} \right\rceil \frac{BT_i}{S_i}\right), \frac{N_aP_{on}BT_i}{S_i}\right)\right] \tag{15}$$

where $E[.]$ is the expectation operator, $Max(.)$ is the maximum operator that provides the maximum value among the two quantities, $\lceil . \rceil$ denotes the ceiling function, T_g is the guard band time between the GATE generation of two ONUs, and Δ is the RTT between an OLT and ONU. Now, this T_{cn} can be computed as follows

$$T_{cn} = Max\left(Min\left(\frac{P_1(T_i)N_aT_g}{1-\rho_n} + (1-P_1(T_i))\Delta, P_1(T_i)\left\lceil \frac{S_i}{T_iR_{on}} \right\rceil \frac{BT_i}{S_i}\right), \frac{N_aP_{on}BT_i}{S_i}\right) \tag{16}$$

where $P_1(T_i)$ is the probability that the cycle length is not governed by RTT (at T_i time) and is given as

$$P_1(T_i) = Prob\left(\rho_n \geq 1 - \frac{N_aT_g}{\Delta}\right) \tag{17}$$

Using (14), (17) can be modified as

$$\begin{aligned} P_1(T_i) &= Prob\left(N_{on} \geq \frac{S_i}{R_{on}T_i} \times \left(1 - \frac{N_aT_g}{\Delta}\right)\right) \\ &= \sum_{j=N_{th}(T_i)}^{N_a} \binom{N_a}{j} P_{on}^{j}(1-P_{on})^{N_a-j} \end{aligned} \tag{18}$$

where $N_{th}(T_i)$ is the number of ONUs after which the cycle length switches to the non-RTT case (at T_i time) given as

$$N_{th}(T_i) = \left\lceil \frac{S_i}{R_{on}T_i} \times \left(1 - \frac{N_aT_g}{\Delta}\right) \right\rceil \tag{19}$$

Now, for the wavelength switching case analysis, we begin with optimal switching condition (given by (2)), according to which the ONU switches to a new wavelength at (or after) T_{NT} time. At T_{NT}, we check whether the current load of the current wavelength of the ONU can accommodate it or not. Let us assume that the maximum load (in bits/sec) per

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[1] The network load that is defined as the sum of offered load by all the ONUs scaled by the ratio of the upstream and downstream line rate.

wavelength is kept below C_m. Therefore, considering the available space (in bits) on the current wavelength (condition given by (5)), the OLT assigns a new wavelength to the ONU subject to the following condition

$$D_j > S_{w,i} \tag{20}$$

Normalizing the above equation with respect to S_i results in

$$\rho_n > \frac{C_m T_{NT}}{S_i} \tag{21}$$

Now, the probability that this condition of wavelength switching is fulfilled is given by

$$P_t = Prob\left(\rho_n > \frac{C_m T_{NT}}{S_i}\right) \tag{22}$$

Using (14), (22) can be further modified as

$$\begin{aligned} P_t &= Prob\left(N_{on} > \frac{C_m}{R_{on}}\right) \\ &\approx \sum_{j=N_t}^{N_a} \binom{N_a}{j} P_{on}^j \times (1 - P_{on})^{N_a - j} \end{aligned} \tag{23}$$

where N_t is the number of ONUs that cross the threshold for C_m (i.e., the number of ONUs after which the switching case activates) and it is given as

$$N_t = \left\lceil \frac{C_m}{R_{on}} \right\rceil \tag{24}$$

Furthermore, the need to switch to a new wavelength is only fulfilled if any such wavelength is available. So, the probability that the OLT finds another wavelength to switch the ONU when the condition given by (21) is fulfilled (considering n ONUs) can be calculated as

$$P_w(n) = 1 - (P_u(n))^{N_w - 1} \tag{25}$$

In the above equation, $P_u(n)$ is defined as

$$P_u(n) = \sum_{j=2N_t-n+1}^{N_a} \binom{N_a}{j} P_{on}^j \times (1 - P_{on})^{N_a - j} \tag{26}$$

Considering this, the probability of switching to a new wavelength with n ONUs is given as

$$P_s(n) = \begin{cases} 0, & \text{if } n < N_t \\ P_t \times P_w(n), & \text{otherwise} \end{cases} \tag{27}$$

Assuming that the switching of wavelength does not exceed by one more than one ONU, the average cycle length (T_{cs}), in this case, is evaluated using (28), as shown at the bottom of the page.

This equation can be explained as the combination of two cases. One case is the cycle length till N_t ONUs, i.e., the non-switching case and second case is the cycle length after N_t ONUs, i.e., the switching case. In (28), the first and second term denotes the cycle length of the non-switching case, and the third term denotes the cycle length when the switching activates.

Furthermore, the average queuing delay for the gated grant sizing scheme (D_{gated}) can be approximately computed as [30]

$$\begin{aligned} D_{gated} &\approx \frac{T_{cs}}{2} + T_{cs} \\ &\approx 1.5 \times T_{cs} \end{aligned} \tag{29}$$

where the first factor $T_{cs}/2$ denotes the packets requesting delay, and the second factor T_{cs} denotes the delay in receiving a GATE message for the requested packets.

Additionally, the worst-case queueing delay (D_{WG}) considering the gated grant sizing scheme is given as

$$\begin{aligned} D_{WG} &\approx D_{PRW} + D_{RGW} \\ &\approx 2T_{cs} \end{aligned} \tag{30}$$

where D_{PRW} is the worst-case packet requesting delay, and D_{RGW} is the worst-case delay in receiving a GATE message for the requested packets. In the worst-case scenario, $D_{PRW} = D_{RGW} = T_{cs}$. Approximately 94% of the user packets faces the worst-case delay given by (30). However, the worst-case delay or the maximum delay (D_{max}) that any user packet faces at the highest load is given as

$$D_{max} \approx 2 \times \left(\frac{N_o B}{N_w L_R} + 2T_g\right) \tag{31}$$

The equation shows that the maximum queueing delay is governed by the buffer size.

V. RESULTS AND DISCUSSIONS

In this section, we evaluate the performance of the proposed online DBWA algorithm in terms of network delay, channel utilization, and time complexity. We compare the performance of the proposed DBWA algorithm with the performance of a state-of-the-art algorithm, namely EFT-OS that is discussed in the next subsection. Additionally, we briefly discuss the OMNeT++ implementation of Super-PON.

$$\begin{aligned} T_{cs} = {} & (1 - P_1(T_{NT}) \times \Delta + N_a T_g \sum_{j=N_{th}(T_{NT})}^{N_t - 1} \binom{N_a}{j} \frac{P_{on}^j (1 - P_{on})^{N_a - j}}{1 - \frac{j R_{on} T_{NT}}{S_i}} + \sum_{j=N_t}^{N_a} \binom{N_a}{j} P_{on}^j (1 - P_{on})^{N_a - j} \\ & \times \left(\frac{N_a (T_g + P_s(j) T_t)}{1 - \frac{N_t R_{on} T_{NT}}{S_i}} P_s(j) + (1 - P_s(j)) \frac{N_a T_g}{1 - \frac{j R_{on} T_{NT}}{S_i}} \right) \end{aligned} \tag{28}$$

A. EFT-OS (STATE-OF-THE-ART DBWA)

Many researchers have proposed the online algorithms to deal with the problem of bandwidth utilization and wavelength allocation in NG-EPON. One such algorithm is EFT-OS that is proposed in [13]. In this algorithm, the authors proposed the use of optimal switching at the OLT similar to the technique considered in this work. However, in this algorithm, the OLT always assigns a new wavelength after every T_{NT} interval (where T_{NT} is given by (2)). The new wavelength is a wavelength whose current grant cycle is finishing earliest.

B. OMNeT++ IMPLEMENTATION OF SUPER-PON

OMNeT++ is a network simulator tool that makes any network simulation much easier because of its extensive network library support. The main modules for simulating Super-PON in OMNeT++ are: OLT module, ONU module, AWG module, power splitter module, and source module. We multiplicate these modules according to our requirements by forming an array of these modules that reuse the same module multiple times. These modules are briefly discussed below:

- The OLT module is a simple module that handles multiple complex tasks. We connect it to the AWG module that transmits (and receives) its messages (or packets) to the power splitter module, which broadcasts messages to the ONU module. The main packets that we handle at the OLT module are: GATE message, REPORT message, and source packets. Using the ONU REPORT message, we generate GATE messages for all ONUs at the interval defined in the IPACT algorithm and allocate wavelength to that ONU using the UBF-BP algorithm. We distinguish the different wavelengths by the different OLT ports assigned to them. Furthermore, we store the incoming source packets in a *queue* (a predefined package present in OMNeT++ library) until they are transmitted to their defined destination.
- The ONU module is connected to the source module and the power splitter module. It is a compound module that consists of two submodules: a buffer module and a basic ONU module. The buffer module stores the incoming source packets using queue and transmits the packets according to the grant assigned by the OLT. The basic ONU module performs two operations. Firstly, it checks whether the GATE message is meant for it or not. Secondly, it checks the wavelength assigned to it. The ONU module then transmits the source packets on the wavelength assigned to it.
- The AWG and power splitter modules are simple connection modules that perform the task of forwarding messages from one connection to another.
- The source module is a simple module. We program it to generate the bursty Pareto traffic at a regular interval and a defined data rate.

Apart from these modules, OMNeT++ project consists of a network descriptor file (known as NED file). In this NED file, we define other network parameters such as the line rate of each wavelength, RTT between different ONUs and the OLT, number of ports at each module, the port connections, and arrays defining the number of times a module is reused.

C. PERFORMANCE ANALYSIS

Using OMNeT++ network simulator tool, we simulate a Super-PON with 64 ONUs, and with the maximum ONU to OLT distance of 25 km. We consider four wavelengths in each direction with the upstream and downstream line rate of 1 Gbps per wavelength (or 2.5 Gbps per wavelength), and 4 Gbps (or 10 Gbps per wavelength), respectively. Furthermore, we assume that the maximum data rate generated by an ONU is 100 Mbps (or 200 Mbps), the ONU buffer is of size 1 MB, the tuning time of an ONU is 1 ms (or 100 μs), a guard time of 1 μs, and the maximum cycle time of 2 ms. Traffic generation is the same as in [32]. The self-similar Pareto traffic has the Hurst parameter of 0.8 and has varying packet sizes (64 to 1518 bytes) in the form of Ethernet frames.

Furthermore, to evaluate the performance of the proposed algorithm in the real-life scenario, we consider asymmetric load conditions at various ONUs. For this, we reckon that 20% of the active ONUs (i.e., 16 ONUs out of 64 ONUs, denoted as high load ONUs) generate 80% of the network traffic and 80% of the active ONUs (i.e., 48 ONUs out of 64 ONUs, denoted as low load ONUs) generate 20% of the network traffic. For such a scenario, any fair algorithm should allocate resources so that low- and high-load ONUs suffer similar delays. To evaluate this fairness, we consider Jain's fairness index [33], according to which the fairness index (F_I) is given as

$$F_I = \frac{(\sum_{m=1}^{M} d_m)^2}{M \sum_{m=1}^{M} d_m^2} \tag{32}$$

where M represents a different number of ONU groups, and d_m represents the average delay value for the m^{th} group. As we are considering two ONU groups (i.e., low load and high load ONUs), the value of F_I varies from 0.5 to 1, where 1 denotes the fairest resource allocation by any algorithm, and 0.5 denotes the unfair resource allocation.

For a PON with the tuning time of 1 ms and 100 μs, the downstream line rate of 4 Gbps, the maximum ONU to OLT distance of 25 km, and the maximum ONU data rate of 100 Mbps, we compare the delay performance of proposed the UBF-BP algorithm with the EFT-OS algorithm in Fig. 4. From the figure, we observe a considerable improvement in the performance in comparison with the state-of-the-art algorithm (EFT-OS). For the LS, a fair grant sizing scheme, with tuning time of 1 ms and at the network load of 1, the delay is close to 120 ms while for the gated grant sizing scheme, it is close to 81 ms. The delay further reduces for the tuning time of 100 μs. Hence, the delay performance of the network is significantly improved by restricting the wavelength

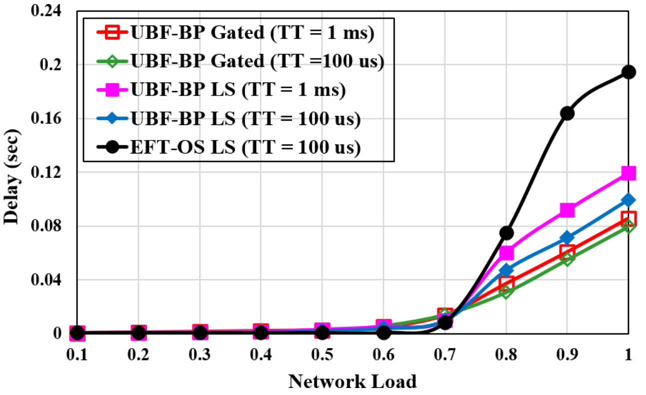

FIGURE 4. Delay vs. network load for different tuning times (TT) with a downstream line rate of 4 Gb/s, reach of 25 km, maximum ONU data rate of 100 Mb/s and symmetric network load (simulation).

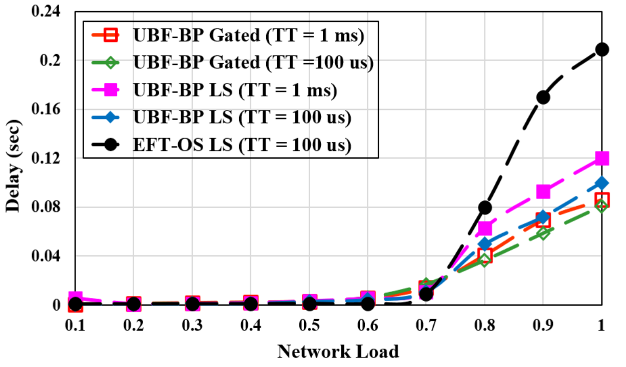

FIGURE 5. Worst-case delay vs. network load for different tuning times (TT) with a downstream line rate of 4 Gb/s, reach of 25 km, maximum ONU data rate of 100 Mb/s, and symmetric network load (simulation).

switching and doing appropriate wavelength assignment using the UBF-BP algorithm.

The worst-case delay is the maximum queuing delay that any ONU suffers at a particular network load, and it is another important factor for the quality of service (QoS) analysis. In Fig. 5, we present the change in the worst-case delay with the network load for the proposed DBWA algorithm (i.e., UBF-BP) and the state-of-the-art DBWA algorithm (i.e., EFT-OS), considering the gated and LS grant sizing schemes and different tuning times. This figure shows the worst-case delay for the scenario considered in Fig. 4. On comparing this figure with the results in Fig. 4, we can see the close similarity between them. The worst-case delay is close to the average delay for the proposed algorithm, i.e., approximately 0.2% higher in the gated scheme and approximately 0.4% higher in the LS scheme. In contrast, the worst-case delay is approximately 6.3% higher than the average delay for the state-of-the-art algorithm. The wavelength switching restrictions and appropriate wavelength assignment that is a part of the UBF-BP algorithm, results in the close proximity of the worst-case delay and average delay in its case. The similar values of d_m for the fairness index calculation (using (32)) and this close proximity in the graphs shows that the UBF-BP algorithm is fair as almost all users suffer a similar delay.

In Fig. 6, we present the packet loss rate comparison of the proposed UBF-BP algorithm with the state-of-the-art EFT-OS algorithm. As channel utilization can be easily calculated from the packet loss rate (channel utilization $\approx$ incoming traffic $-$ packet loss rate), it is an important aspect for the online algorithms. We can deduce from the figure that the packet loss rate of the proposed scheme is notably lower than the state-of-the-art scheme. Hence, the use of the UBF-BP algorithm improves channel utilization for Super-PON.

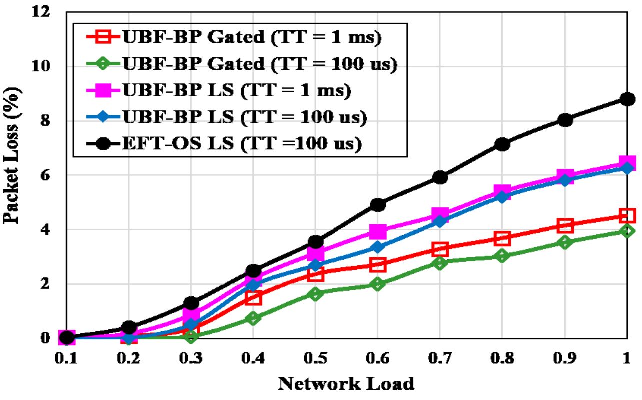

FIGURE 6. Packet loss rate vs. network load for different tuning times (TT) with a downstream line rate of 4 Gb/s, reach of 25 km, maximum ONU data rate of 100 Mb/s and symmetric network load (simulation).

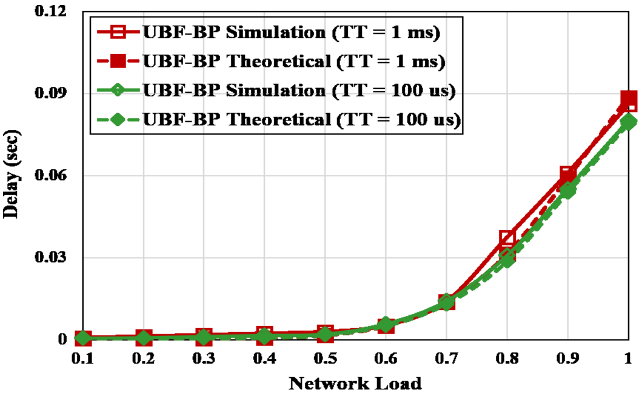

FIGURE 7. Theoretical and simulation case delay vs. network load for the UBF-BP algorithm for different tuning times (TT) with a downstream line rate of 4 Gb/s, reach of 25 km, maximum ONU data rate of 100 Mb/s and symmetric network load.

In Fig. 7, we compare the simulation and theoretical (shown using the dashed line and obtained using (29)) delay performance of the proposed UBF-BP scheme considering the gated grant sizing scheme. From the figure, we observe that for both the tuning times (100 μs and 1 ms), the simulation and theoretical cases are similar. This shows the correctness of the proposed UBF-BP algorithm.

To observe the delay performance of the proposed algorithm at a higher channel downstream line rate (10 Gbps) and

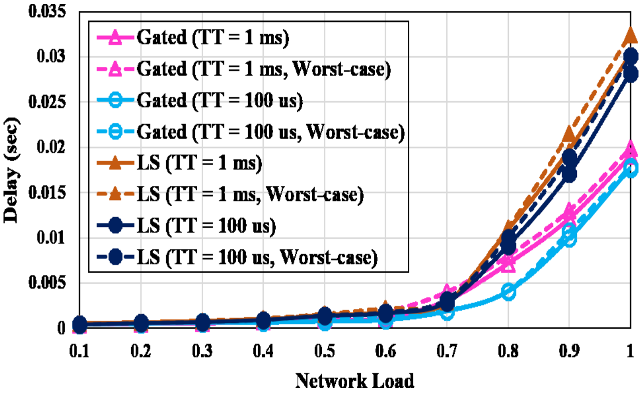

FIGURE 8. Delay vs. network load for the UBF-BP algorithm for different tuning times (TT) with a downstream line rate of 10 Gb/s, reach of 25 km, maximum ONU data rate of 200 Mb/s, and symmetric network load (simulation).

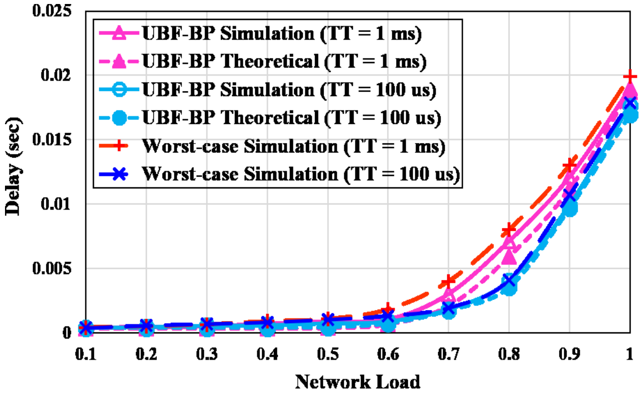

FIGURE 10. Theoretical and simulation case delay vs. network load for the UBF-BP algorithm for different tuning times (TT) with a downstream line rate of 10 Gb/s, reach 25 km, maximum ONU data rate of 200 Mb/s considering the gated grant sizing scheme, and symmetric network load.

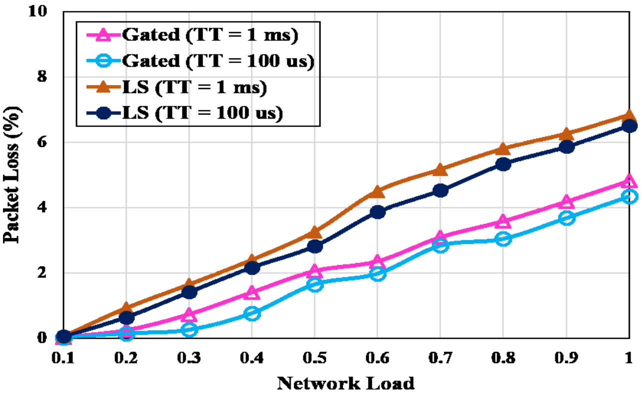

FIGURE 9. Packet loss rate vs. network load for the UBF-BP algorithm for different tuning times (TT) with a downstream line rate of 10 Gb/s, reach of 25 km, maximum ONU data rate of 200 Mb/s and symmetric network load (simulation).

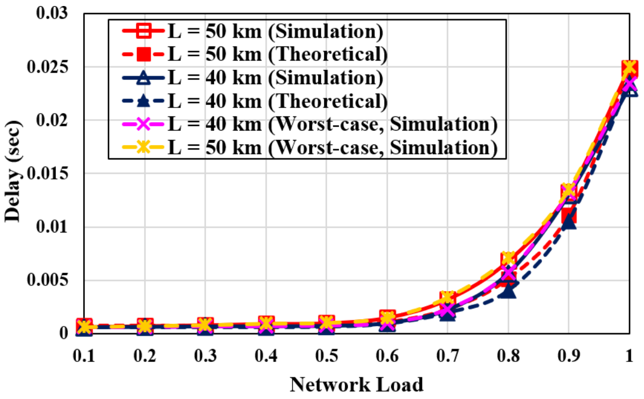

FIGURE 11. Theoretical and simulation case delay vs. network load for the UBF-BP algorithm using the gated scheme and different reach (L) with a downstream line rate of 10 Gb/s, tuning time of 1 ms, maximum ONU data rate of 200 Mb/s, and symmetric network load.

a higher ONU data rate (200 Mbps maximum), we present Fig. 8. In the case of the LS grant sizing scheme, as the network load approaches 1 (with the tuning time of 1 ms), the average delay approaches 30 ms while in the case of the gated grant sizing scheme the average delay is close to 18 ms. Hence, with such an excellent delay performance, we can say that the proposed algorithm can cope with the higher data rates. Additionally, the nearness of the worst-case delay (shown using dashed lines) with the average delay shows that the proposed algorithm treats all users with equal fairness. Furthermore, Fig. 9 presents the packet loss rate for this Super-PON channel. From the figure, we observe that the channel utilization is considerably high (greater than 93% for the LS scheme and greater than 95% for the gated scheme) even at the network load of 1.

In Fig. 10, we compare the delay values obtained from the theoretical analysis (shown using the dashed line) and the simulation considering a downstream line rate of 10 Gbps, tuning time of 1 ms and 100 μs, and the gated grant sizing scheme. From the figure, we observe that the theoretical values are similar to the simulation values. This similarity validates the credibility of the proposed analytical model. Furthermore, the worst-case delay is approximately 2.9% higher than the average delay (in simulation). This infers that the queuing delay is almost the same for all users. Note that as the worst-case theoretical results (obtained using (30)) are similar to the worst-case simulation results, we only show the worst-case simulation delay in Fig. 10 and in Fig. 11, avoiding figures becoming cluttered.

In Fig. 11, we show the impact of increasing the maximum distance between the ONU and OLT (or reach) on the delay performance of the Super-PON considering the gated grant sizing approach. At the reach of 40 km and the network load of 0.1, the average delay is close to 600 μs while for the reach of 50 km, the average delay approaches 750 μs. Similarly, at the network load of 1 and reach of 40 km, the average delay is close to 23 ms while for the reach of 50 km, the average delay approaches 24 ms. Therefore, from this figure, we can say that the proposed algorithm UBF-BP performs well, even with the increased network reach. Furthermore, the similarity between the theoretical (shown using the dashed line) and simulated values shows the correctness of the

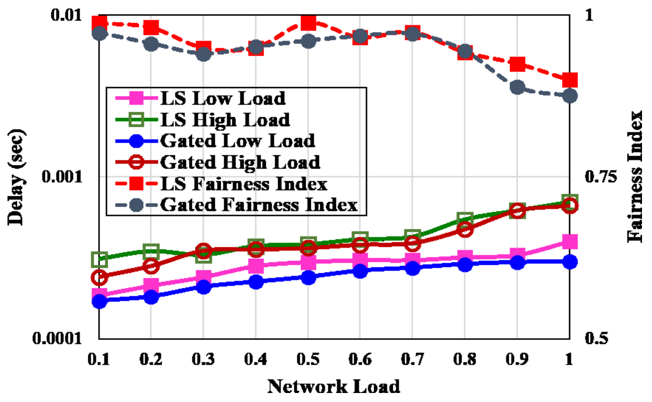

FIGURE 12. Delay shown using vertical right axis and fairness index shown using left vertical axis and dashed line for the UBF-BP algorithm with a downstream line rate of 10 Gb/s, reach of 25 km, tuning time of 100 μs, maximum ONU data rate of 200 Mb/s, and asymmetric network load (simulation).

proposed algorithm. Additionally, the closeness of the worst-case with the average delay in this scenario infers the fairness of the proposed algorithm in resource distribution.

To show the impact of the average delay on the fairness index, we consider asymmetric network load and present Fig. 12 and Fig. 13. In Fig. 12, we consider the tuning time of 100 μs, and in Fig. 13, we consider the tuning time of 1 ms. From these figures, we can verify the fact stated earlier that the LS grant sizing scheme is fairer than the gated grant sizing scheme. However, the fairness index for both cases is above 0.87, which shows that the UBF-BP algorithm is fair. Additionally, from these figures, we can also deduce that whenever the low load and high load delay are closer to each other, the fairness improves (at 0.5 network load in Fig. 12 and at 0.8 network load in Fig. 13). In contrast, as they move away from each other, the fairness decreases (at 1 network load in Fig. 12 and Fig. 13). Furthermore, restricting the maximum grant in the LS grant sizing scheme results in higher delay than the gated grant sizing scheme.

To illustrate the trade-off between the packet loss rate and fairness index, we present Fig. 14, where the packet loss rate is shown using vertical right axis and fairness index is shown using vertical left axis and dashed line. For the gated grant sizing scheme, the maximum packet loss rate is approximately 4.5%, while the maximum packet loss rate is close to 8% for the LS grant sizing scheme. The fairness index is close to 0.875 (the lowest value) at the network load of 1 for all considered scenarios.

D. COMPLEXITY ANALYSIS

We compute the time complexity of the proposed DBWA using the pseudo code given in Algorithm 1. From this pseudo-code, we note that the operations that are adding to the time complexity are **For** and **If-Else** loops. The time complexity order of **For** loop is $O(n)$ where n is the number of times the loop is executed. For calculating the wavelength with the maximum available capacity in line 17, we use **For** loop and its time complexity is $O(N_w)$ (i.e., $n = N_w$). Furthermore, in the case of **If-Else** loop, the time complexity order is the highest among both the cases. Additionally, in line 7 to 12, we perform a binary search operation to procure the best fit wavelength. The time complexity for this search is $O(log(N_w))$. Now, considering these facts, the time complexity of the UBF-BP algorithm for the worst-case is $O(N_w + log(N_w))$. As $N_w = 4$, the worst-case time complexity (T_c) is given as

$$\begin{aligned} T_c &= O(4 + log(4)) \\ &\approx O(4.602) \end{aligned}$$

This value of T_c indicates that the UBF-BP algorithm have a light computational load.

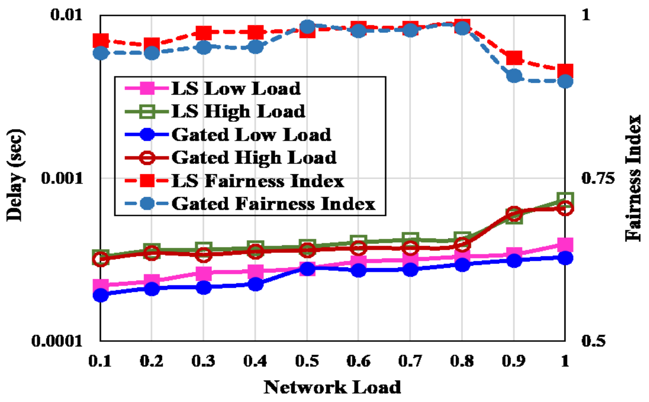

FIGURE 13. Delay shown using vertical right axis and fairness index shown using left vertical axis and dashed line for the UBF-BP algorithm with a downstream line rate of 10 Gb/s, reach of 25 km, tuning time of 1 ms, maximum ONU data rate of 200 Mb/s, and asymmetric network load (simulation).

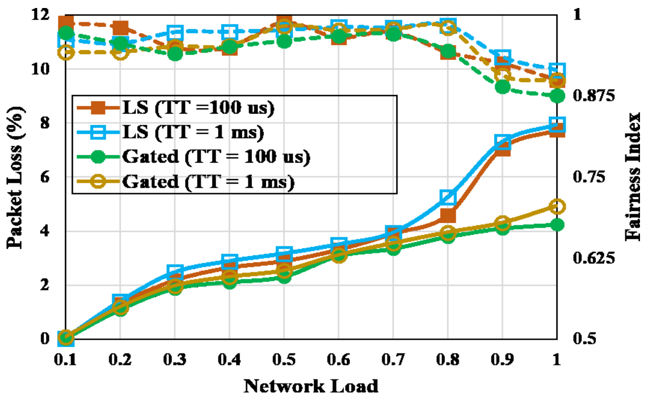

FIGURE 14. Packet loss rate shown using vertical right axis and fairness index shown using left vertical axis and dashed line for the UBF-BP algorithm considering different tuning times (TT) with a downstream line rate of 10 Gb/s, reach of 25 km, maximum ONU data rate of 200 Mb/s, and asymmetric network load (simulation).

VI. CONCLUSION

In this work, we proposed a novel online DBWA algorithm for Super-PON, namely UBF-BP. The proposed algorithm employs the updated best fit bin-packing algorithm for wavelength allocation that, in turn, overcomes the inefficiencies of wavelength utilization and switching. Furthermore, to establish a fair bandwidth allocation, we use the LS grant sizing scheme with the UBF-BP algorithm. This scheme dispenses a surplus grant in the case of large bandwidth requirements. The simulation results show that the proposed algorithm has a lower delay (approximately 50% less) and a higher channel utilization (approximately 5% more) than the state-of-the-art algorithm (EFT-OS). Additionally, the results indicate that the proposed algorithm imparts excellent network performance even at a high channel line rate and high network reach. We also analyze the worst-case delay, another important QoS factor. The nearness of the worst-case delay with the average delay shows that nearly all users suffer a similar delay.

To prove the fairness of the proposed algorithm and to show the trade-off between delay and fairness, we considered asymmetric network load and evaluated the fairness using Jain's fairness index. The lowest value of this fairness index is 0.875 for all considered scenarios, which substantiates that the proposed algorithm treats all low load and high load users with equal fairness. Additionally, the increased delay in the case of the LS grant sizing scheme is justified by the improved fairness that it brings to the network. Furthermore, the low complexity of this algorithm makes it a scalable and efficient DBWA algorithm. Moreover, to authenticate the correctness of the proposed algorithm, we also proposed an analytical delay model. The indistinguishable difference between the simulation and analytical results verified the credibility of the proposed algorithm. Though the DBWA algorithm is proposed in the context of Super-PON, other polling based networks like time and wavelength division multiplexed PON and light-fidelity (LiFi) can also use its principles to accrue delay efficiency.

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