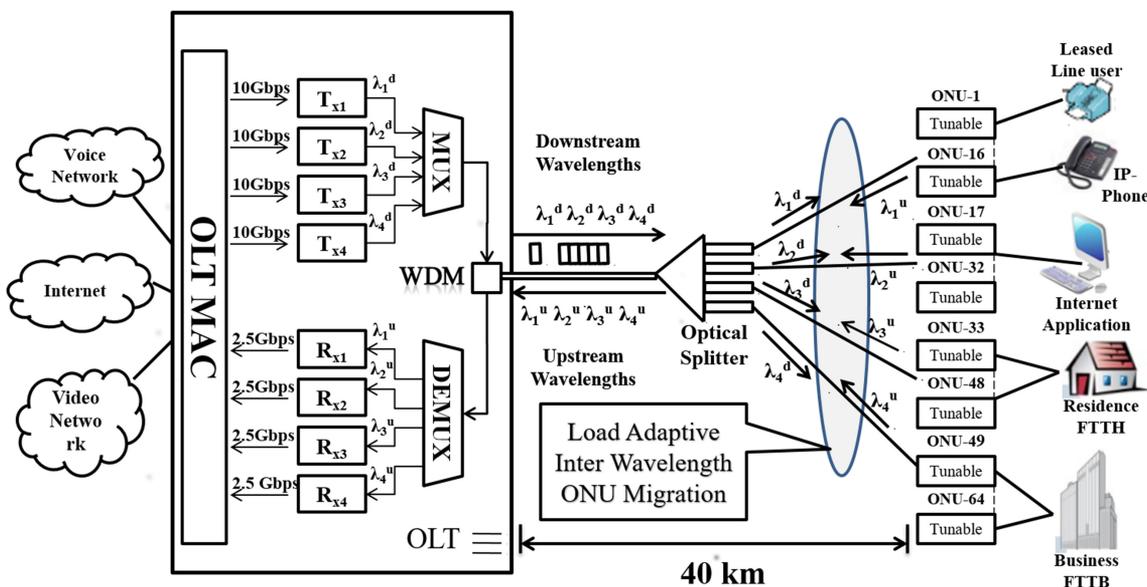


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Kamran Ali Memon
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Kamran Ali Memon ¹, Qi Zhang,¹ Rizwan Aslam Butt ²,
Khalid Hussain Mohammadani ¹, Muhammad Faheem ³, Noor ul
Ain ¹, Feng Tian ¹, and Xiangjun Xin ¹

¹State Key Laboratory of Information Photonics and Optical Communications, School of Electronic Engineering, Beijing University of Posts and Telecommunications, 100876, China

²Department of Electronic Engineering, NED University of Engineering, Karachi, Pakistan

³Department of Computer Engineering, Abdullah Gul University, Kayseri 38080, Turkey

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Abstract: This study presents a dynamic inter wavelength migration scheme for the optical network units (ONUs) employing linear regression machine learning method to equalize the traffic volume on all the wavelengths in time and wavelength division multiplexed passive optical network (TWDM PON). The proposed traffic-adaptive wavelength and bandwidth assignment (TA-WBA) scheme not only decreases upstream traffic delays but also offers 2.3% and 30% less delay on the wavelengths balancing the excessive load and 7% less upstream bandwidth waste, when evaluated against other load-balancing scheme.

Index Terms: TWDM PON, traffic-adaptive, load balancing, ITU compliant, DWBA, PLOAM, US traffic delay, and bandwidth utilization.

1. Introduction

The demand for high-speed data services such as Netflix, Bit Torrent, YouTube, and Hulu is rapidly growing, and the overall trend suggests that global internet traffic would hit hundreds of exabytes around 2021 [1]. The FSAN recommended time and wavelength division multiplexed passive optical network (TWDM PON) as a sole solution for the next-generation passive optical network(NG-PON) to meet the needs and research on networks providing over 40 Gbps to meet such relentless growth in traffic demand [2]. Fig. 1 explains the ITU compliant TWDM PON architecture. It uses WDM to keep multiple wavelengths in the single optical distribution network (ODN), with each wavelength being shared by multiple ONUs. ITU TWDM PON standard G.989.3 recommends four to eight wavelengths to be operated in downstream (DS) in L band ranging from 1590 to1610 nm, all with a data rate of 10 Gb/s and from 1520 to1540 nm in C band for upstream (US) with a data rate support of 2.5 Gb/s or 10 Gb/s data. Each ONU in TWDM PON utilizes a tunable transceiver for US/DS data transfer/reception on suitable US/DS wavelengths. This promotes the gradual bandwidth enhancement, load balancing and minimizes the ONU inventory issues for TWDM PON.

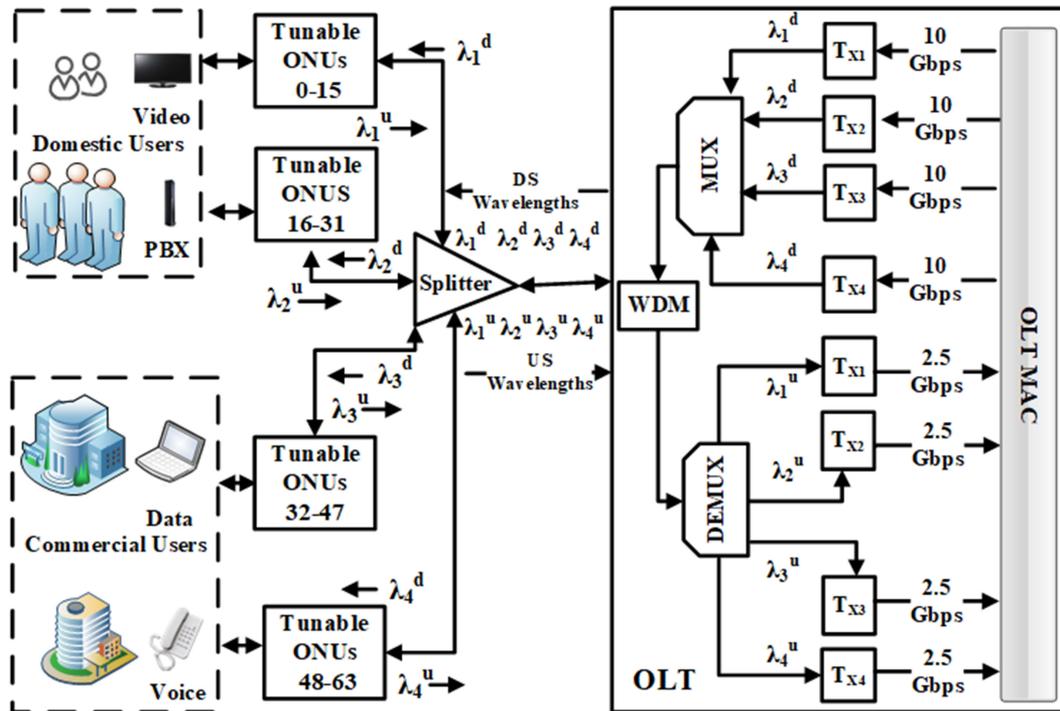


Fig. 1. Showing typical TWDM PON architecture.

With extended reach and higher split ratio, TWDM-PON users, i.e., domestic users to commercial office users, reflect a great variety when it comes to the bandwidth demand. For instance, the domestic users' traffic is expected to be minimal in the morning, due to users being out to their work, and at peak in the evening, as they will be back home. This heterogeneity trend in the use of traffic could give rise to a traffic load imbalance on the various TWDM PON wavelengths serving residential and industrial areas. This may result in an overuse of a wavelength, leading to significant delays; on the other side, other wavelengths may be idle, resulting in upsetting the balance in bandwidth usage. Consequently, an efficient wavelength switching and load balancing mechanism is essential to switch ONUs operating under heavily loaded wavelengths to lightly loaded ones before congestion occurs. The designing of such dynamic wavelength and bandwidth assignment (DWBA) depends on several factors like ONU transceiver tuning time, switching and load balancing methods. Several DWBA algorithms are reported, but mostly using the IEEE compliant carriers in each wavelength of TWDM PON. For instance, the investigation in [3] utilizes 10-EPON to compare the dynamic and static wavelength allocation mechanism in the TWDM PON. It utilizes tuning gate signal in its dynamic wavelength assignment (DWA) implementation to enable ONU to tune to other wavelengths. The investigation outcomes indicate that the allocation of dynamic wavelengths and smaller tuning time significantly reduces US delays. Another study in [4] presents an efficient load-balancing algorithm with no loss of US frames in wavelength tuning procedure. However, as reviewed in [5], this load balancing mechanism needs a large buffer memory at the ONUs and causes large tuning time which is not suitable for TWDM PON. The very first hitless wavelength tuning scheme experiment was presented in [6] with an OLT and two ONUs. DWBA in [7] distributes the traffic to each wavelength fairly and suffers less from both wavelength reallocations and the tuning time drawbacks with a high messaging overhead. The studies in [8], [9] experimentally verified such a scheme and reduced the messaging overhead between OLT-ONU for the wavelength switching by delaying the ONU relocation until traffic load exceeds a pre-defined threshold.

For wavelength switching, the main factor to consider is the load metric, i.e., the criteria for the switching or choice of wavelengths in DWA procedures. Since the traffic is a random process, it is

difficult to fix all wavelengths at some absolute traffic load in the DWA procedure. Keeping in mind, the study in [10] categorized the total varying traffic load on the wavelengths in three zones, i.e., lightly loaded, balanced and heavily loaded. These zones have traffic thresholds based on which ONUs were transferred in-between zones. This method eliminated frequent ONU tuning among distinct wavelengths arising from fluctuations in the user traffic load. However, this was preliminary research work, which ignored multi-media service constrains, tuning priorities and details about pre-set threshold values. Therefore, this study tries to fill this gap by proposing an optimized traffic-aware DWBA scheme. This work is inspired by the earlier similar studies [11], [12] presented for traffic load balancing in TWDM PON, which opted for an extreme end traffic balancing approach. In these approaches, the ONU with the highest traffic load of the most burdened wavelength is transferred to the other wavelength having the minimum traffic load. However, such approaches do not optimize the traffic load distribution between all the wavelengths. Therefore, this study presents a load proportional traffic load-balancing scheme, i.e., Traffic Adaptive Wavelength and Bandwidth Assignment (TA-WBA) scheme, in which multiple ONUs are migrated simultaneously to keep the overall traffic load balanced on the entire set of the wavelengths. In this paper, Section 2 explains the proposed TA-WBA scheme; Section 3 discusses the simulation parameter setting. Section 4 and Section 5 presents the results and conclusion remarks respectively.

2. Traffic Adaptive Wavelength and Bandwidth Assignment Scheme (TA-WBA)

The flexible ONU switching among wavelengths in TWDM PON promotes the seamless bandwidth upgrade and maintenance, redundancy, and load balancing. For the ONU switching process, OLT channel termination (CT) offers MAC for the all ONUs' US traffic and represents each wavelength with unique US wavelength channel ID (UWLCH-ID). In the switching process, ONU (n) first meets some triggering criteria set by OLT and then coordinates with OLT CT (i) for switching from one UWLCH-ID(x) to other UWLCH-ID(y). In the complete switching process, OLT uses inter-channel-termination protocol (ICTP) messages for tuning out ONU (n) from UWLCH-ID(x) and tuning into UWLCH-ID(y) under OLT CT (J). Both OLTs keep allocating US bandwidth slots to ONU (n) in the handshake process, so ONU (n) continues to receive US PLOAM messages for the successful switch over. In case OLT (J) accepts ONU (n), it replies with Tune-Response (ACK) message on UWLCH-ID(y). If there is a rejection, destination replies with Tune-Response (NACK) message, and ONU (n) trigger ROLLBACK via UWLCH-ID(x) to end the switching process [13]. This wavelength switching mechanism adds the tuning delay in the US transmissions.

2.1 Traffic Load Based Classification of Wavelengths

Since the arrival of traffic is the real time process; therefore, the traffic load may not be the same on all wavelengths in TWDM PON, therefore, a regression-based machine-learning model is used to learn the traffic trend of each wavelength. The model is based on the customized regression model given by Eq. (1). The model is used to compute the predicted traffic load $\mu_L(i)$ for each wavelength $\lambda(i)$. Where m_λ represents the gradient of regression line (RL) and C_y represents the y-axis intercept for RL. The m_λ and C_y are computed from Eq. (2) and Eq. (3) using the recorded traffic load values ($Q(i)$) recorded during the last service interval (SI) for each $\lambda(i)$, where 'M' is the total active wavelengths of TWDM PON being used by the OLT.

2.2 Dynamic Wavelength Switching Scheme

The TA-WBA algorithm is explained in a 3-step flowchart in Fig. 2, available in the following sections.

2.2.1 Calculation of Error Vectors: In order to have a balanced distribution of traffic on all the wavelengths, the regression model in section 2 is used to predict the desired traffic load value ($Load_{predicted}[i]$) for each $\lambda(i)$. In step-1, the error vector $V_{Err}[i]$ is computed for each $\lambda(i)$ by taking

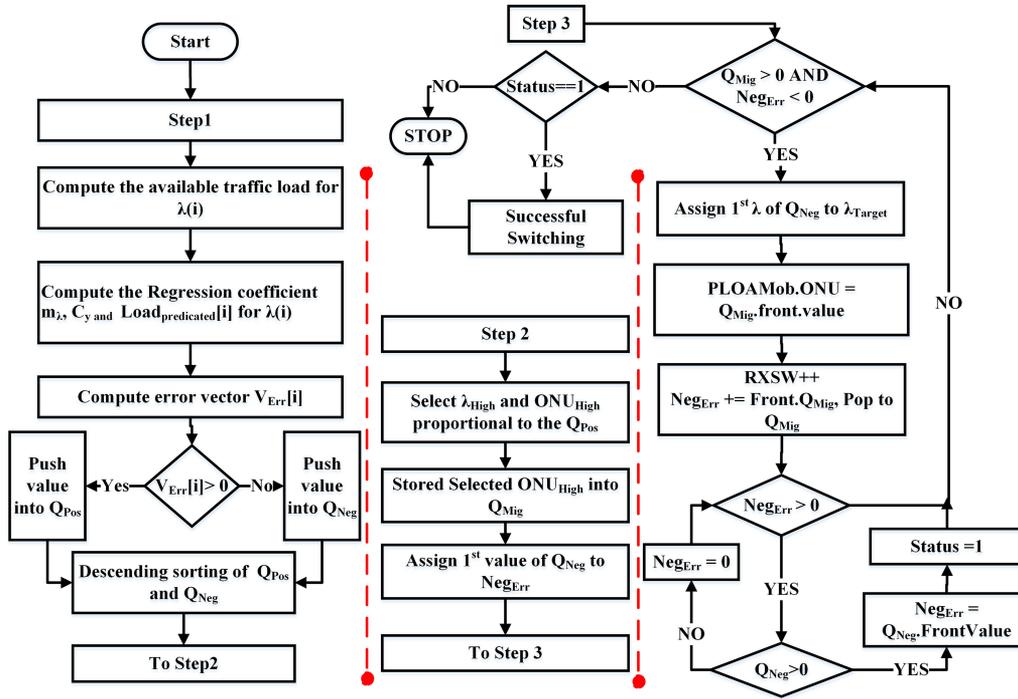


Fig. 2. TA-WBA algorithm flow.

the difference of the $Load_{predicted}[i]$ and the sum of the queue reports of the ONUs of $\lambda(i)$. The error values will be positive if $\lambda(i)$ is overloaded and negative if $\lambda(i)$ is underloaded. The positive errors along with the wavelength are stored in a structure element $ErrEL$ and then added to positive and negative queues termed as Q_{Pos} and Q_{Neg} respectively. Finally, both the queues are sorted in descending order. The service interval (SI) parameter is set to 10, which allows the algorithm to execute at once during SI. The algorithms take the ONU traffic demand and traffic load on the all wavelengths into consideration.

$$\mu_L(i) = m_\lambda * \lambda(i) + C_y \quad (1)$$

$$m_y = \frac{\sum_{i=1}^M \left(\left(Q(i) - \frac{\sum_i Q(i)}{M} \right) * \left(\lambda(i) - \frac{\sum_{i=1}^M \lambda(i)}{M} \right) \right)}{\sum_{i=1}^M \left(\lambda(i) - \frac{\sum_{i=1}^M \lambda(i)}{M} \right)^2} \quad (2)$$

$$C_y = \left(Q(i) - \frac{\sum_i Q(i)}{M} \right) - m_\lambda * \left(\lambda(i) - \frac{\sum_{i=1}^M \lambda(i)}{M} \right) \quad (3)$$

2.2.2 Formation of ONU Migration Queue: In step-2, the heavily loaded ONUs proportional to the positive error of each wavelength i.e., λ_{High} in Q_{pos} are selected and stored in a vector Q_{Mig} . The proposed scheme picks the target least loaded wavelength λ_{Target} from Q_{Neg} and then selects all the ONUs one by one from the Q_{Mig} and keeps on offloading these ONUs to λ_{Target} until its error value becomes zero.

2.2.3 Inter-Wavelength ONU Migration: The switching of ONUs from one wavelength to another settles the traffic load on the entire set of wavelengths and is performed in step-3. The offloading process is initiated by triggering the Tuning_Control messages for the concerned ONUs. For this purpose, all the PLOAM messages are queued up in the Q_{PLOAM} from where the DS TWDM process collects all the queued up messages and sends them on the DS $\lambda(i)$ depending upon target ONU

number. The Tuning Control message also contains the target wavelength number to which ONU is required to switch to. The switching process continues until either the Q_{Neg} or Q_{Mig} is exhausted. However, frequent switching increases the bandwidth waste and US delay due to the addition of tuning time. In order to minimize the bandwidth and US delay, the algorithm has an inbuilt traffic load threshold value to start, i.e., the algorithm will only execute when the value of the cumulative traffic load of all the ONUs is above 25% (approximately 38000 bytes) of the traffic. This means either a single wavelength is fully topped up or that two wavelengths are topped up 50 percent. This condition triggers the load-balancing algorithm to execute. The RXSW flag is also incremented whenever a Tuning_Control message is queued up to control duplicate switching for the same ONU. Thus, the step-1 is only executed after an SI if the previously imitated switching process has been completed. The completion of the switching process for an ONU is indicated by the reception of Tuning_Response message from the ONU. On each reception of Tuning_Response message, the RXSW flag is decremented.

3. Simulation Parameter Setting

In this study, the 64 ONUs were considered, and the wavelength set was restricted to four to reduce the computational load in OMNET++. The DS link rate for each wavelength was set to 10 Gbps, and the US line rate was set to 2.5 Gbps like in [14]. The ONU to OLT distance is 40 km resulting in a round trip time of 400 μ s with 200 Mbps Line-rate between OLT to ONU. In each ONU all the four traffic classes, also termed as traffic containers (TCONTs); Type-1 (T1) to Type-4 (T4) TCONTs defined by ITU for PON [13] are considered. The bandwidth reservation ration for T1, T2, and T3 traffic TCONTs in each ONU is set at 20 Mbps, 90 Mbps, and 90 Mbps bandwidth respectively. For T4, a 90 Mbps capacity is set for the best effort case. The simulation scenarios use an SI value of 10 and 1 MB size US buffer for T2, T3 and T4 traffic classes [15]. The tuning time for the laser is fixed to 1ms [3]. The network uses a traffic generator that follows the Poisson distribution. Traffic is generated using an exponential function based on the required traffic load by calculating the inter-arrival time (IAT), Computed using Eq. (4). The generator first determines the traffic arrival rate per ONU (\mathcal{R}_{ONU}) computed using Eq. (4) for both US and DS. Where the *Link_Rate* value for DS and US is for TWDM PON is 155530 bytes and 622120 bytes respectively, the \mathcal{F}_{avg} is the average packet size of the generated traffic frames and the total number of active ONUs is represented by 'j'. The *Traffic_Load* is the ratio of total traffic bytes sent by all the ONUs and the *Link_Rate*. Normally, this ranges from 0 to 1 but may surpass 1, indicating an overloaded network condition. Similar to earlier studies such as [12], [16], [17], the overloaded condition was not simulated as in this condition the US delays for T1 and T4 increase exponentially for all the DWBA schemes due to unavailability of bandwidth, thus, there is little information available to compare the performance.

$$IAT = Exponential \left(\frac{1}{\mathcal{R}_{ONU}} \right) \quad (4)$$

$$\mathcal{R}_{ONU} = \frac{Traffic_Load * Link_Rate}{j * \mathcal{F}_{avg}} \quad (5)$$

We execute each simulation for an hour, as the mean IAT variation stays within a 95 percent confidence interval during this duration. The traffic load is changed from 0.01 to 1. For each ONU, a different traffic generator instance is created. All the ONUs are assumed to have same service level agreement. The traffic ratio is kept to 10 percent T1 traffic and 30% T2, 30% T3 and 30% T4 traffic as also in [18]. Initially, the ONUs are distributed equally to all the TWDM wavelength; the ONU_{ID} from 0 to 15 are assigned $UWLCH_{ID}(0)$, the ONU_{ID} from 16 to 31 are assigned $UWLCH_{ID}(1)$, the ONU_{ID} from 32 to 47 are assigned $UWLCH_{ID}(2)$ and the ONU_{ID} from 48 to 63 are assigned $UWLCH_{ID}(3)$. To simulate an unbalanced traffic load scenario, the traffic load generated for ONU_{ID} 0 to 31 is reduced by 20%, while for ONU_{ID} 32 to 63 it is raised by 20%. These traffic configurations among the ONUs will equalize the traffic generator's overall network load.

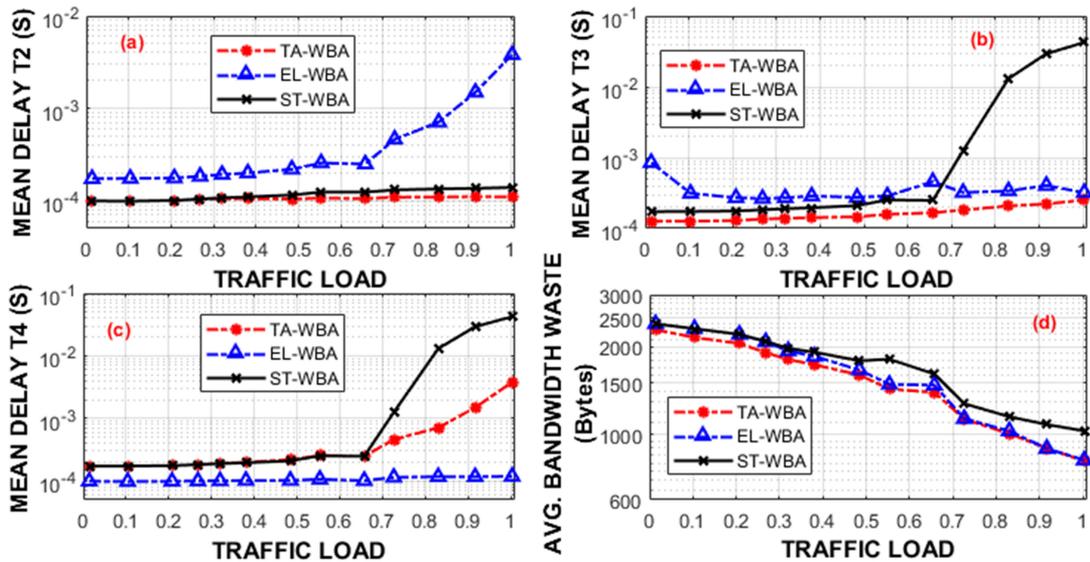


Fig. 3. Upstream delay for TCONTs: (a) T2, (b) T3, (c) T4 and (d) bandwidth waste per ONU.

4. Results and Discussion

The US delay and bandwidth utilization performance of the TA-WBA scheme was compared with the results of ST-WBA scheme that uses fixed wavelength assignment [14] and with extreme load balancing WBA (EL-WBA) scheme that balances traffic load by swapping the most high and least loaded ONUs [11], [14]. The Time complexity of ST-WBA was observed to be $O(n)$ while for EL-WBA and TA-WBA, it was found to be $O(n \log(n))$. In case of mean US delay for class T2 traffic in Fig. 3(a), EL-WBA comparatively offers more delay due to its extreme balancing approach. Whereas proposed TA-WBA and ST-WBA offer nearly similar delays on low load. However, as the traffic load increases, the adaptive traffic approach works well and offers 21% less delay as compared to ST-WBA on maximum load. Fig. 3(b) confirms the fact that ST-WBA approach is not capable of handling the imbalance in the traffic requiring assured and non-assured bandwidth, i.e., T3 traffic class. Out of the two WBAs, EL-WBA delay pattern is inconsistent and performs poorly even when compared to ST-WBA up to half of the maximum load. Overall, Proposed TA-WBA scheme provides surplus bandwidth to the non-assured portion of T3 on the highly loaded wavelengths and offers the least US delays than other WBAs. Due shortage of surplus bandwidth, the ST-DBA approach causes an exponential increase in delay of overloaded wavelengths which leads to an exponential increase in the mean US delay of traffic class T3 after the traffic load of 0.65.

In the case of T4 traffic class depicted in Fig. 3(c), the proposed scheme exhibits marginally greater delay compared to EL-WBA. At the start with low loads, the ST-DBA scheme offers the same performance as of TA-WBA, but its delay starts increasing exponentially after the load of 0.65 due to a shortage of surplus bandwidth for the highly loaded wavelengths. However, due to the efficient balancing of TA-WBA scheme, the bandwidth availability increases for higher priority traffic classes; T2 and T3, which results in a decreased amount of bandwidth for T4 traffic class. Due to this trade-off, T4 delay for TA-WBA is higher compared to EL-WBA approach. However, this trade-off is acceptable as the maximum delay remains under 20ms, which is in the acceptable range for the best-effort services. If there is a situation that there is an unused bandwidth available at the end of TA-WBA scheme, this amount of bandwidth is efficiently utilized by equally distributing it among all the ONUs.

Fig. 3(d) shows the US bandwidth waste results for three WBA schemes. Due to the wavelength switching mechanism, TA-WBA still offers some bandwidth waste, but it is quite low compared with

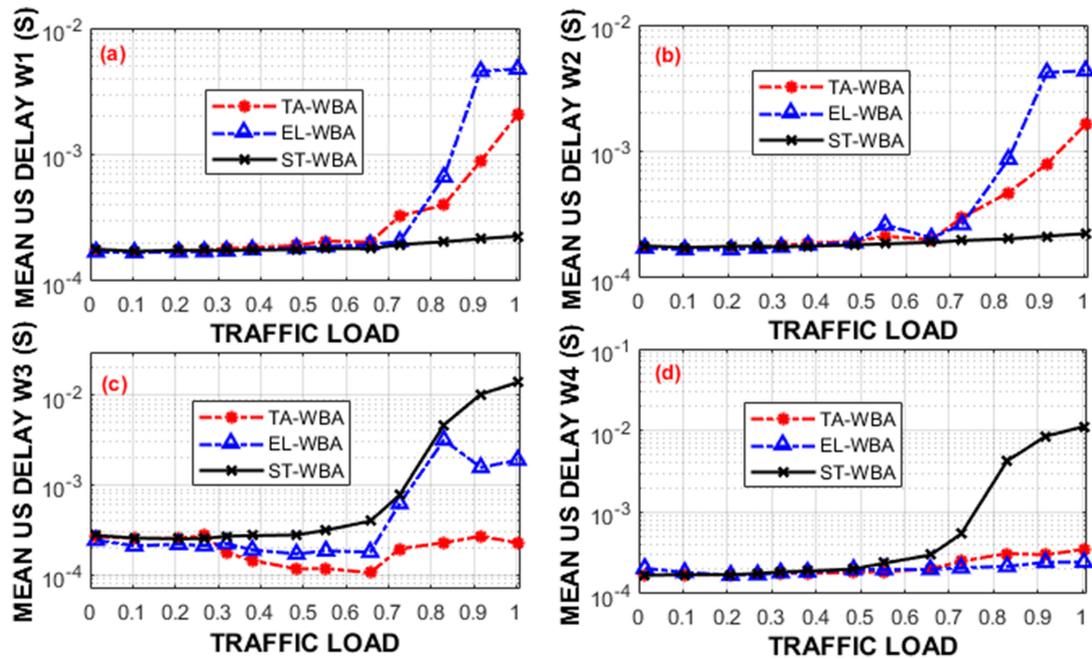


Fig. 4. Upstream delay for wavelengths: (a) W1, (b) W2, (c) W3 and (d) W4.

ST-WBA scheme. At a particular point, the bandwidth waste is suddenly reduced to zero value. Both balancing algorithms EL-WBA and TA-WBA perform efficiently to save bandwidth waste and behave neck to neck in results.

The results of US delay on wavelengths (W1-W4) shown in Fig. 4(a) to Fig. 4(d), decide the switching and balancing capability of the algorithms. Based on the asymmetric traffic scenario used, imbalance in the W3 and W4 is stabilized by W1 and W2. As a reason, US delay on W1, W2 is increased after 0.5 of the load, US delay on W3, and W4 are significantly reduced. Specifically for W1 and W2, ST-WBA offers less US delay due to fixed allocation nature, whereas proposed TA-WBA has above all satisfactory performance when compared to both. At maximum load value, TA-WBA offers 2.3% less delay on W1 and 30% less delay for W2 when compared with the results of EL-WBA scheme. Thus, the TA-WBA scheme can substantially decrease the delays of heavily loaded wavelengths by swapping the additional traffic volume from the W3 and W4 efficiently with a slight rise in the delays of lightly loaded W1 and W2 wavelengths.

5. Conclusion

This study presents a novel self-load-balancing DWBA for ITU compliant TWDM PON with 40 Gbps DS and 10 Gbps US. The Proposed scheme employs a linear regression-based machine-learning algorithm to track the ONUs requiring high bandwidths and their respective overloaded wavelengths. The results of TA-WBA scheme completely outperform the ST-WBA, whereas against EL-WBA shows up to 5%, 40% and 8% lesser US delays for T2, T3 and T4 TCONTs at higher loads. TA-WBA puts 2.3% and 30% less delay penalty on lightly loaded wavelengths for balancing the excessive load and 7% less bandwidth waste. The proposed scheme will be useful for TWDM PON operators in offering the incremental bandwidth upgrade (Pay-as-you-Grow). It can also help them to increase revenue by accommodating more T4 traffic users with best effort bandwidth commitment with an efficient dynamic traffic load balancing.

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