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Supporting Diverse Customers and Prioritized Traffic in Next-Generation Passive Optical Networks

Naureen Hoque
University of Nebraska - Lincoln, nau.hoque@gmail.com

SUPPORTING DIVERSE CUSTOMERS AND PRIORITIZED TRAFFIC IN NEXT-GENERATION PASSIVE OPTICAL NETWORKS

by

Naureen Hoque

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SUPPORTING DIVERSE CUSTOMERS AND PRIORITIZED TRAFFIC IN NEXT-GENERATION PASSIVE OPTICAL NETWORKS

Naureen Hoque, M.S.

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Adviser: Byrav Ramamurthy

The already high demand for more bandwidth usage has been growing rapidly. Access network traffic is usually bursty in nature and the present traffic trend is mostly video-dominant. This motivates the need for higher transmission rates in the system. At the same time, the deployment costs and maintenance expenditures have to be reasonable. Therefore, Passive Optical Networks (PON) are considered promising next-generation access technologies. As the existing PON standards are not suitable to support future-PON services and applications, the FSAN (Full Service Access Network) group and the ITU-T (Telecommunication Standardization Sector of the International Telecommunication Union) have worked on developing the NG-PON2 (Next Generation PON 2) standard.

Resource allocation is a fundamental task in any PON and it is necessary to have an efficient scheme that reduces delay, maximizes bandwidth usage, and minimizes the resource wastage. A variety of DBA (Dynamic Bandwidth Allocation) and DWBA (Dynamic Wavelength and Bandwidth Allocation) algorithms have been proposed which are based on different PONs (e.g. EPON, GPON, XG-PON, 10G-EPON, etc.). But to our knowledge, no DWBA scheme for NG-PON2 system, with diverse customers and prioritized traffic, has been proposed yet. In this work, this problem is addressed and five different dynamic wavelength and bandwidth allocation (DWBA) schemes are proposed. First, mixed integer linear programming (MILP) models are developed to minimize the total delay of the high priority data. Due to the MILP's high computational complexity, heuristic algorithms are developed based on the MILP model insights. The five heuristics algorithms are: No Block-Split Heuristic (NBH), Equal Block-Split Heuristic (EBH), Priority Based No Block-Split Heuristic (P-NBH), Priority Based Equal Block-Split Heuristic (P-EBH), and Priority Based Decider Block-Split Heuristic (P-DBH). Six priority classes of requests are introduced with the goal of minimizing the total delay for the high priority data and to lessen the bandwidth wastage of the system. Finally, experiments for the performance evaluation of the five DWBA schemes are conducted. The results show that P-NBH, P-EBH, P-DBH schemes show a 47.63% less delay and 30% of less bandwidth wastage on average for the highest priority data transmission than the schemes without priority support (NBH and EBH). Among these five schemes, NBH method has the highest delay, whereas EBH and P-EBH waste more bandwidth than the other schemes. P-DBH is the most efficient among the five because this scheme offers the lowest delay for high priority data and the minimum bandwidth wastage for lower priority ones.

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Chapter 1

Introduction

The demand for high-speed data services is constantly rising. By 2021, it is estimated that the data requirements of access network would exceed 3.3 Zettabyte [1], and more than 26 billion networked devices and these connections would produce approximately thrice the traffic generated in 2015 [2]. Due to high capacity, cost-effectiveness, and coverage potential, Passive Optical Networks (PONs) are becoming a suitable and promising access network option. Recently the deployment of XGS-PON [3] and 10G-EPON [4] have been reported which are capable of providing 10 Gbps in the downstream and 1/2.5/10 Gbps in the upstream direction. Next Generation Passive Optical Network 2 (NG-PON2) supports a total network throughput of 40 Gbps [5]. According to the latest updates to standard G.989.2, enabling up to a total of 80 Gbps capacity have been approved and a discussion on bit-rate increment from 10 Gbps per channel to 25 Gbps have taken place in the ITU-T [6]. The Full-Service Access Network (FSAN) group has started working on the specifications of the future broadband network under NG-PON2 standard.

In NG-PON2, the optical line terminal (OLT) allocates bandwidth and specifies the number of the transmission windows (TWs) on the wavelengths to the optical network unit (ONU). After receiving the grant, the ONUs start sending data frames to the OLT. This is termed as dynamic wavelength and bandwidth allocation (DWBA).

At each wavelength, a guard band is used to separate the data frames of two different ONUs to avoid collision. If a grant is transmitted through a single wavelength, then one guard band is used after its transmission process. But there would be four times of guard band used if the same grant is transmitted over four wavelengths. Although, a single channel transmission provides less bandwidth wastage, it increases the total transmission delay and for multiple wavelength allocation, it is the inverse.

To achieve maximum bandwidth utilization, it is required to have an efficient DWBA in the NG-PON2 system. Otherwise, improper resource allocation might lead to the degradation in the overall network performance as there would be more delay and increased bandwidth wastage. An efficient dynamic wavelength and bandwidth allocation (DWBA) scheme allows the system to include additional customers to the network and to support enhanced services. It is a method of assigning wavelength and bandwidth to the ONUs based on their traffic contracts and the usage patterns. The standard for NG-PON2 (ITU-T G.989) describes the single wavelength bandwidth allocation, but it leaves the multiple wavelengths allocation issue to the implementers' preferences as long as the base cases, which are discussed in the standard specification, are handled [5].

In this work, the focus is on the wavelength assignment part, assuming that the system applies conventional DBA method described in the standard ITU-T G.989. It is also assumed that the same DBA method is applied for every wavelength. Considering these mentioned assumptions, we propose five DWBA algorithms with the goal of minimizing the total delay of the high priority data and reducing the bandwidth wastage of the system. The experiment results show that the small-sized or low-priority data should be transmitted over a single wavelength to minimize the bandwidth wastage and the high priority ones over multiple wavelengths as parallel transmission reduces the transmission delay.

1.1 Motivation

It is already mentioned that Passive Optical Networks (PON) is the most appropriate and promising candidate for the future access network to support diverse and rapidly increasing traffic. PON started with a 155 Mbps upstream and 155/622 Mbps downstream rate, but now the capacity is from 2.5 Gbps to a 40 Gbps.

It is important to assign the resources efficiently to maximize the bandwidth utilization. This leads to satisfy low latency, to add more customers, and to support enhanced services in the NG-PON2 system. It is also identified that an efficient DWBA algorithm provides better load-balancing and reduces power-consumption [7]. Many studies have been done to design the dynamic wavelength and bandwidth allocation (DWBA) based on next-generation EPON or generalized TWDM-based systems [8, 9, 10, 11]. We discuss those in Section 2.4. To our knowledge, no DWBA method specifically for NG-PON2 system has been proposed yet. We propose five different schemes for allocating wavelengths dynamically in an NG-PON2 system with the motivation of minimizing the total delay of the high priority data and reducing the bandwidth wastage. The detailed description of both the mathematical models and heuristic algorithms are presented in Chapter 3.

1.2 Contribution

This work has three main contributions as described below:

- In this study, as there are no Dynamic Wavelength and Bandwidth Allocation methods for NG-PON2 system that have been proposed already, five different wavelength allocation schemes are proposed in this work.

- Six different classes of priorities are introduced where the requests with higher priority are handled first. Also, it is proposed that the small-sized or low-priority data would be transmitted by a single wavelength to minimize the bandwidth wastage and the high priority ones by multiple wavelengths as parallel transmission to reduce the transmission delay.

- To avoid unnecessary bandwidth waste by excessive guard times, it is proposed that the small-sized or low priority data should be transmitted over single channel. The minimum data-size that should be allowed to be transmitted over multiple wavelengths is obtained through the experiments.

1.3 Outline

This document is structured as follows:

- Chapter 2 provides the background and the details of the Passive Optical Networks, Next Generation NG-PON2 Passive Optical Networks, and the existing Dynamic Wavelength & Bandwidth Allocation schemes for different PONs.

- The problem description provided in Chapter 3 with the mathematical model and the heuristic algorithms.

- Chapter 4 provides the details of the implementation of the proposed schemes and the analysis of the results.

- Chapter 5 presents the conclusions and the future work.

Chapter 2

Background

2.1 Passive Optical Networks (PON)

An access network is a telecommunication network that connects the users to their service providers through the carrier network. It is a set of access links and devices connected by the optical access transmission systems.

Optical access network elements are the OLT (Optical Line Terminal) and the ONU (Optical Network Unit). The OLT and ONU are installed by the service providers. The OLT is located in the CO (Central Office) of the service provider and the ONUs are at the users' ends.

There are two types of transmission - Upstream and Downstream. The transmission flow from the ONUs to the OLT is the upstream. The downstream refers to the transmission from the OLT to ONUs. The OLT sends the data frames to the router/switch or a splitter. Fig. 2.1 (left) depicts that the Active Optical Network uses router or switch. The router or switch transfers the frames specific to the user. Contrarily, Passive Optical Network uses splitter as it is shown in Fig. 2.1 (right). The splitter sends the same set of frames to all the ONUs which means the data is transmitted by broadcasting. Each ONU filters out the frames specific to the user and discards the rest.

Active Optical Network

Active appliances are used in an Active Optical Network (AON) to control the network connection distribution or to provide connections to some particular users. The active elements are routers, switches, multiplexers, etc. Using active components allows the network to support longer distances, but it requires high deployment and management costs.

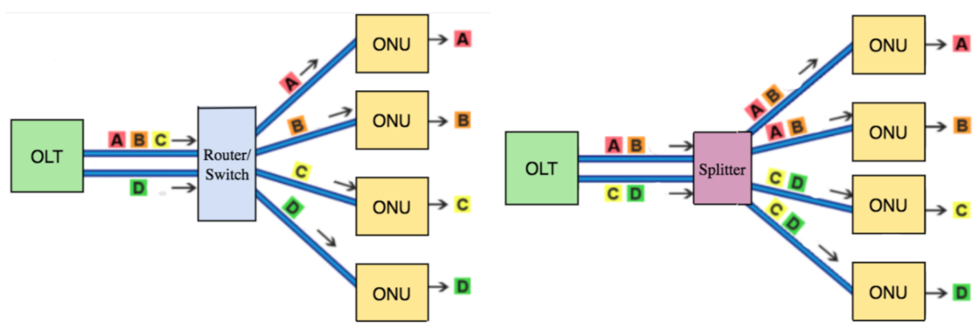

Figure 2.1: Active (left) and Passive (right) Optical Networks

Passive Optical Network

A passive optical network uses optical splitters instead of electrically powered devices. Thus, it support less distance than AON. PON has lower deployment and operational costs.

This system brings fiber optic communications system to the last mile. This is known as Fiber to the x (FTTx). It is a generalized form and x refers on where the PON terminates, for example, FTTB (building), FTTC (cabinet), FTTD (desktop), FTTH (home), FTTN (node), FTTO (office), and FTTP (premises). In 1995, the FSAN (Full Service Access Network) group was created with the telecommunications service providers and the vendors. The ITU-T (Telecommunication Standardization Sector of the International Telecommunication Union) was chosen by the FSAN group to standardize the PON systems. The ITU-T and the IEEE (The Institute of Electrical and Electronics Engineers) developed different standards of passive optical networks [12].

2.1.1 Different Standards of Passive Optical Networks

The first PON system was Asynchronous Transfer Mode or APON. Later, another PON came into the industry - Broadband PON (BPON). The successor GPON is mostly deployed in the FTTH networks. Table 2.1 shows the standard names, creation year, up/downstream rates of different PONs.

Table 2.1: Different Standards of PON

PON	**Name**	**Standard**	**Year**	**Upstream**	**Downstream**
APON	ATM	Former G.983	1995	155Mbps	155/622Mbps
BPON	Broadband	G.983	1998	155/622Mbps	155/622Mbps
GPON	Gigabit	G.984	2004	1.25Gbps	2.5Gbps
EPON	Ethernet	IEEE 802.3ah	2004	1Gbps	1Gbps

APON - Asynchronous Transfer Mode/ATM PON

APON standard was developed in 1995 with upstream and downstream rate of 155 Mbps and 155/622 Mbps respectively. It was able to include IP data, video, and Ethernet services to the business and the residential users. It was the most low-cost broadband PON fiber solution.

BPON - Broadband PON

BPON is a standard which is based on APON. With the characteristics of APON, this standard includes the support for Wavelength Division Multiplexed (WDM) system.

Due to low-cost and easy deployment, there was a rapid development and popularity of Ethernet technology. This became the catalyst for Ethernet-PON and this also made ATM-based PONs went out-of-the-market.

EPON - Ethernet PON

EPON is developed by IEEE and based on 802.3 Ethernet. All Ethernet characteristics are supported by EPON. To initiate and maintain the connectivity, it uses the dynamic bandwidth algorithm (DBA) and multipoint control protocol (MPCP) [13].

GPON - Gigabit PON

Gigabit Passive Optical Networks or GPON is defined by the standard ITU-T G.984. It is a point-to-multi point access system. This uses Time Division Multiple Access (TDMA) to assign bandwidth grants to the ONUs. Each ONU can receive 2.5 Gbps downstream rate. The upstream rate is lower than the maximum rate of 1.25 Gbps as all the ONUs share it at the same time [14].

2.1.2 FSAN Working Group and Roadmap

The FSAN has been working on the standards that are beyond GPON. They put these standards under the category of next-generation PON (NG-PON). FSAN has specific groups for handling the NG-PON standard and the previous standard related tasks.

The FSAN group has two active task group now: Operation and Engineering Task Group and Next Generation PON (NG-PON) Task Group.

(i) Operation and Engineering Task Group:

In a multiple vendor system, it is required to have a complete interoperability. The Operation and Engineering Task Group is responsible to enable this in the PON systems. Previously this group worked on APON, BPON, and GPON systems' interoperability and now they are working on XG-PON.

(ii) Next Generation PON (NG-PON) Task Group:

The objective of this working group is to design the future system of the PON with enabling the smooth migration between systems. The current focus of this group is Next Generation PON-2 (NG-PON2).

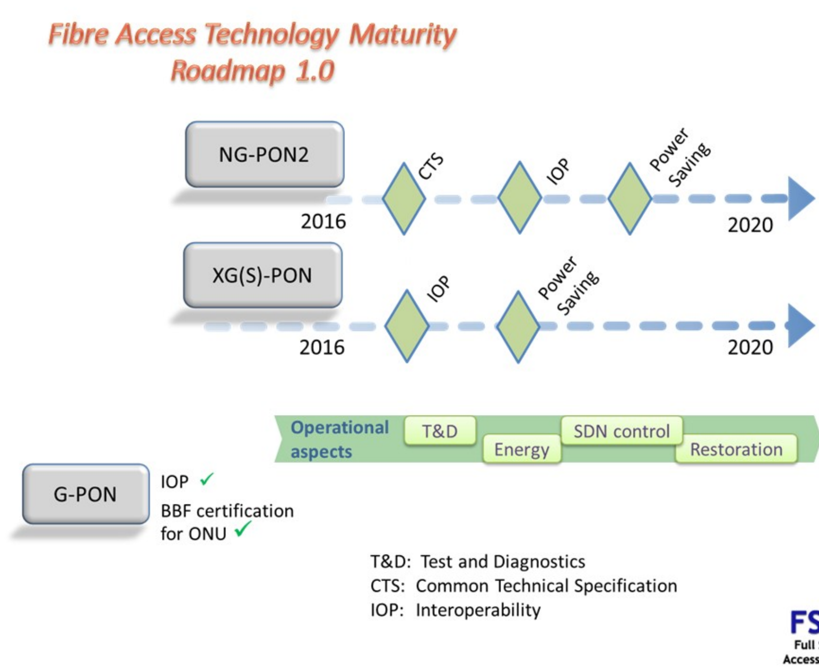

Figure 2.2: FSAN Standards Roadmap 1.0 (released November 2016)[15]

FSAN released a Roadmap in November 2016 to explain the future system setting and technology expansion. This roadmap (Fig. 2.2[15]) mostly was realized as originally planned as XG-PON was first brought out as a standard in 2010. The NG-PON2 standard was published by the end of 2015.

The network operators in FSAN released a Fiber Access Technology Maturity Roadmap in July 2017 (Fig. 2.3[15]) which is named as FSAN Standards Roadmap 2.0. FSAN's expectation is to advance the existing standards by 2020. One apparent way to advance the present standard is to implement 25 Gbps rate at every wavelength. This would enable up to 200 Gbps of capacity of a system with eight wavelengths. After 2020, FSAN will focus on the FOAS (Future Optical Access System). This roadmap also pinpoints the technologies that will influence the future PONs: SDN, NFV, 5G, IoT, network convergence.

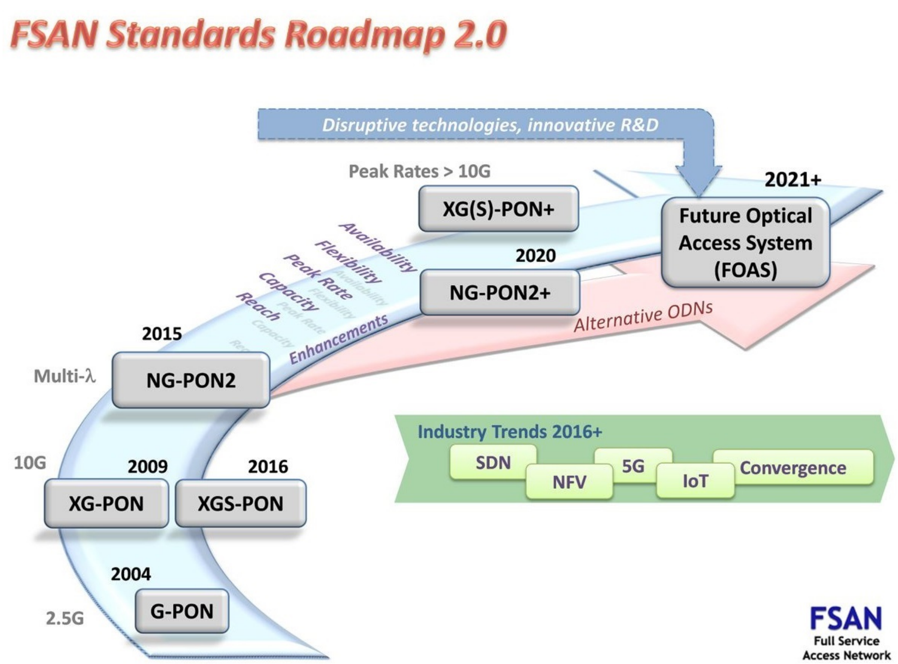

Figure 2.3: FSAN Standards Roadmap 2.0 (released July 2017)[15]

2.2 Next-Generation Passive Optical Networks (NG-PON)

According to FSAN and ITU-T, the next-generation PONs are divided into two stages: NG-PON1 and NG-PON2.

2.2.1 NG-PON1

In 2009 ITU-T presented a version of G-PON with the 10 Gbps downstream rate. This GPON version is known as XG-PON. The X stands for Roman number ten. Then in 2016, another version named XGS-PON was developed which is 10Gbps in both the direction - up and downstream. These XG-PONs are considered as the NG-PON1.

NG-PON1 is the coexistence with the current GPON and also known as XG-PON. This also has two phases: XG-PON and XGS-PON. The GPON with 10 Gbps rate is known as the XG-PON. The standard XGS-PON has the rate of 10 Gbps in both the up and down stream.

The high bandwidth offered by the NG-PON1 leads to support more users in the network. The demand for high speed keeps increasing despite of 10 Gbps rate of NG-PON1.

2.2.2 NG-PON2

In 2015, International Telecommunication Union (ITU) developed a telecommunication network standard known as Next Generation Passive Optical Network or NG-PON2 which supports multiple wavelengths and each of them can be up to 10 Gbps in both up/downstream. The throughput can reach 40 Gbps with four wavelengths [5]. In the future, there is a possibility to offer eight wavelengths that would provide up to 80 Gbps. NG-PON2 provides wider coverage, higher bandwidth, and high data-rate. It is also proposed as the long-term solution of optical access networks by FSAN.

Table 2.2: NG-PON2 Standards

Series	Title
G.989	40Gbps Capable PON: Definitions, abbreviations and Acronyms
G.989.1	40Gbps Capable PON: General requirements
G.989.2	40Gbps Capable PON: Physical media dependent (PMD) layer specification
G.989.3	40Gbps Capable PON: Transmission convergence layer specification
G.988	ONU management and control interface (OMCI) specification

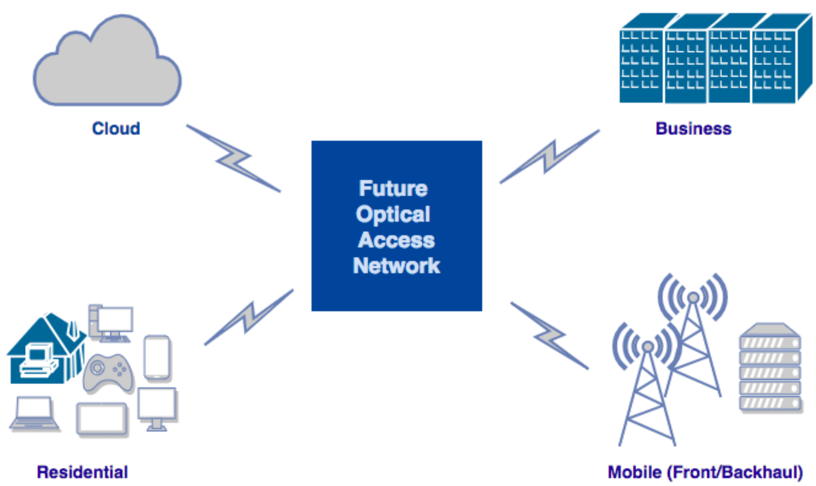

Figure 2.4: Future Optical Access Network

It is expected that the future optical access network would be more flexible, bandwidth and energy efficient, eligible to handle multiple service supported infrastructure (Fig. 2.4). NG-PON2 has all these above mentioned characteristics. The high growth of mobile broadband has increased the need for backhaul capacity. Also the plan of Cloud-RAN deployment requires high capacity for mobile fronthaul. These both have influenced the NG-PON2 deployment. The Table 2.2 shows the NG-PON2 standards provided by ITU-T.

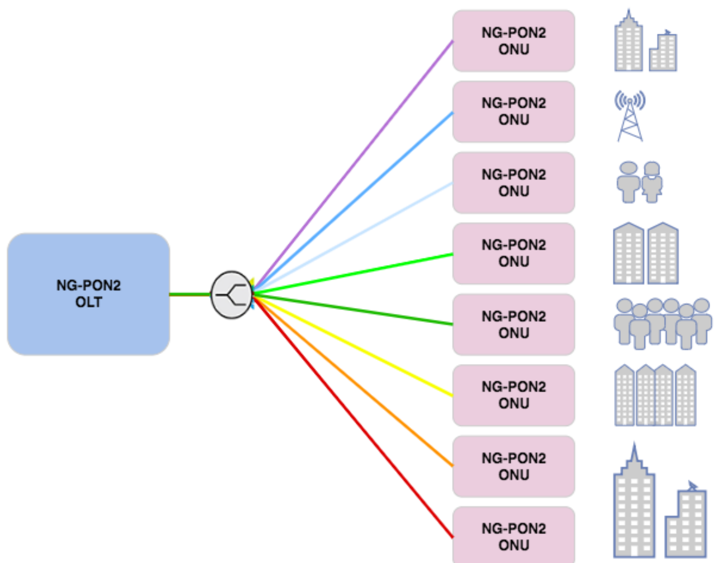

Figure 2.5: Multiple-wavelength NG-PON2 OLT connected to ONUs

NG-PON2 Technology

Many studies have been carried out which discussed the prospective technologies for the NG-PON2: TDM (Time Division Multiplexing), WDM (Wavelength Division Multiplexing), OCDM (Optical Code Division Multiplexing), OFDM (Orthogonal Frequency Division Multiplexing), TWDM (Time and Wavelength Division Multiplexing) [16], [17], [18], [19], [20], [21]. Time and Wavelength Division Multiplexing (TWDM) was selected as the technology for NG-PON2 by the FSAN group in 2012 [22]. TWDM offers better system performance, lower power consumption, and maintenance cost [23].

TWDM is the hybrid of Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM). There are two possible approaches of resource allocation in TWDM-based PON: static and dynamic. The wavelengths and the bandwidth are specifically defined for each ONU in a static system and they always remain the same. In contrast, in the dynamic approach, the wavelength can be tuned and bandwidth can be assigned as required by the ONUs at any time [24, 25].

2.3 Resource Allocation in NG-PON2

2.3.1 Bandwidth Allocation in NG-PON2

The access network is a shared network and the allocation of the upstream bandwidth is done by the OLT. As the distance between ONU and OLT may not be the same for all ONUs, each ONU can have distinct transmission delay. Through a PLOAM (Physical Layer Operations, Administration and Maintenance) message, the OLT sets a register in an ONU. This is used to balance its transmission delay in regard to the other ONUs of the system. This process of delay equalization is named as *Ranging*.

Principles of Allocation

There are some basic principles of bandwidth allocation mentioned in the NG-PON2 standard. According to that, the general case traffic generator (D) is represented as $< R_F, R_A, R_M, X_{AM}, P, \omega >$ with the following constraints:

$$R_M \geq R_F + R_A$$

$$R_M \geq R_F + R_A > 0, \ if \ X_{AM} = NA$$

$$R_M > R_F + R_A \geq 0,\ if\ X_{AM} = BE$$

With the basic stability conditions:

$$\sum_i ({R_F}^i + {R_A}^i) \leq C$$

The traffic descriptor are expected to satisfy:

$${R_F}^* + {R_A}^* = \sum_i ({R_F}^j + {R_A}^j)$$

$$\max_i {R_M}^j \leq {R_M}^* \leq \sum_j {R_M}^j$$

Here, i and j are two different traffic descriptor. C is the capacity, excluding all the overheads. R_F, R_A, R_M are fixed, assured, maximum bandwidth respectively and all of them are greater than or equal to 0. Fixed bandwidth is the reserved part of the capacity. It is allocated to the traffic flow whether there is any demand or not. Maximum bandwidth is the upper limit that is allowed to be allocated under any condition. X_{AM} is the indicator of eligibility for extra bandwidth requirement. This indicator is composed of three options: none, assured and best-effort bandwidth. P and ω are the priority and weight of a best-effort bandwidth allocation. ${R_G}^i(t)$ is the assigned guaranteed bandwidth. As long as the basic stability condition is satisfied, the guaranteed bandwidth grant would be:

$${R_G}^i(t) = min\{{R_F}^i + {R_A}^i,\ max\{{R_F}^i, {R_L}^i(t)\}\}$$

Types of Allocation

To use a designated time intervals for upstream transmission, the OLT provides permission to each ONU which is known as *Grant*. The OLT assigns the grant to each ONU after the ranging process is done. This grant allocation process can be static or dynamic. In static method, the grant sizes are assigned to the ONUs at the beginning. But, in a dynamic process, the OLT recalculates the grant size for each ONU every cycle. The OLT generates the bandwidth maps (BWmaps) which defines the size of the grants.

The major disadvantage of Static Bandwidth Allocation (SBA) is that bandwidth can not be utilized efficiently, although it is a much simpler method of resource allocation than the Dynamic Bandwidth Allocation (DBA). A DBA scheme improves TWDM PON upstream bandwidth utilization, the network operator can add more subscribers to it, and the users have the benefit of enjoying different enhanced services.

Types of DBA

Status Reporting (SR-DBA) and Non-Status Reporting (NSR-DBA) are the two types of DBA methods.

In Non-Status Reporting (NSR-DBA), each ONU gets some extra amount of bandwidth continuously. The OLT observes all the ONUs and if any ONU sends idle frames, the OLT reduces its allocation. Similarly, if an ONU does not send idle frame, then the bandwidth grant is increased.

In Status Reporting (SR-DBA) method, the OLT requests the buffer status from all the ONUs. Each ONU responds with a report that contains the buffer status with the information of the data which are waiting in the specified time slots. By using this report, the OLT recalculates the bandwidth allocation and sends new the BWmap to the ONUs. The ONU sends an idle frame to the OLT to inform that its buffer is empty. Then the OLT uses that extra portion of grant to other ONU which requires more bandwidth.

2.3.2 Bandwidth and Wavelength Allocation in NG-PON2

The general requirements of an NG-PON2 systems are of four logical functions: wavelength assignment, wavelength tuning, wavelength resource administration, and wavelength channel performance supervision [26].

Wavelength Assignment

The initial downstream and upstream wavelengths of an ONU should automatically be assigned to the OLT.

Wavelength Tuning

Wavelength tuning is a great characteristic in NG-PON2 system. It is possible to tune some ONUs from a heavily loaded wavelength to an idle one. The system load would be balanced by this process. On the other hand, during the light traffic periods, the OLT can turn some its ports off which leads to power savings.

Wavelength Resource Administration

The system supports resource administration. The wavelength availability and allocation information is provided to the resource administration. The available bandwidth and wavelengths are used for dynamic wavelength and bandwidth allocation (DWBA).

Wavelength Channel Performance Supervision

The wavelength channels in an NG-PON2 system have to be maintained properly to ensure the system's sound health. Troubleshooting has to be done whenever any wavelength related defects is detected.

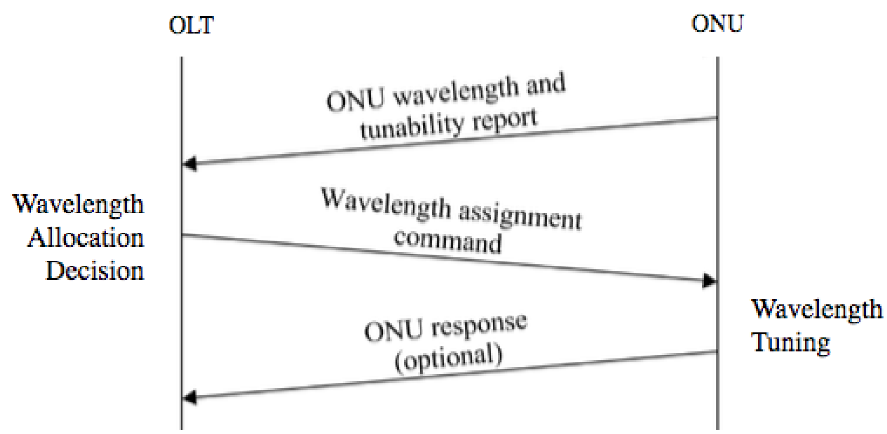

Figure 2.6: Wavelength Allocation Message Exchange

Fig.2.6 depicts message exchange between the OLT and an ONU for wavelength allocation. ONU sends its wavelength and grant requirement to the OLT. Based on that information, the OLT decides if the ONU would get single/multiple wavelength or if the ONU requires to shift in other lightly loaded wavelength. Then, the OLT sends a message to the ONU providing the decision. The ONU tunes the wavelength if it is decided by the OLT and then replies with a report containing updated status.

2.4 Related Work

Although there is no specific Dynamic Bandwidth Allocation (DBA) or Dynamic Wavelength and Bandwidth Allocation (DWBA) scheme that is proposed for NG-PON2 system yet, an extensive study has been done on the scheme based on other standards (GPON, EPON, XG-PON, etc) for this thesis.

2.4.1 Dynamic Bandwidth Allocation (DBA) in PONs

To assign bandwidth to each ONU, the static bandwidth allocation (SBA) is the simplest way. But the problem is, there would be higher delay and bandwidth wastage whenever the traffic is high [27]. Moreover, with SBA the bandwidth cannot be assigned to a specific traffic class inside ONU. Therefore, a passive optical networks (PON) system's performance and potential is dependent on a DBA scheme. An efficient DBA scheme is responsible for utilizing the bandwidth and reducing the delay.

As it has already been discussed in section 2.3.1 that the Dynamic Bandwidth Allocation (DBA) scheme can be of two types: Status Reporting (SR-DBA) and Non-Status Reporting (NSR-DBA). Between these two types, SR-DBA is considered as better with regard to bandwidth utilization and total delay [11]. Most of the studies have been done based on SR-DBA for ITU PONs [10]. The first DBA algorithm, named GIANT, for GPON was proposed in 2006 [8]. It is in the category of SR-DBA. Later, there have been several (both new algorithm and extended version of GIANT scheme) DBA proposed. One extension of the GIANT algorithm is the Efficient Bandwidth Utilization (EBU-DBA) for XG-PON system that presents remarkable improvement in the delay [9]. Allocation with Colorless Grant (IACG) DBA scheme shows higher delay and frame loss than EBU and lower delay than GIANT [28], [29]. One DBA scheme, GPON Redundancy Eraser Algorithm for Long-Reach (GREAL), does not utilize the excess bandwidth to support added traffic [30] and has higher delay that EBU and IACG algorithms [28]. Another DBA scheme, Improved Bandwidth Utilization (IBU), does not compatible for the XG-PON system [31].

N. E. Frigui et al. introduce a bandwidth allocation scheme that uses customer traffic use pattern which they find by doing clustering analysis [32]. They used K-means and DBSCAN clustering methods to have the pattern of usage. To categorize the users' traffic usage by a time-period, the authors used assignment Index (AI) with the range of 0 to 1. The K-means shows a better classification results compared to DBSCAN. They extend their work [33] and include a forecasting module based on the GM(1,1) model to have the predict the extra bandwidth that can be utilized.

A Virtual Dynamic Bandwidth Allocation (vDBA) is proposed that allows multiple operators to access the same platform and it is an XGS-PON DBA [34]. Later the authors propose a solution [35] that does not require any additional communication between the virtual network operators and the extra bandwidth of ONU can be transferred to the other ONU.

2.4.2 Dynamic Wavelength and Bandwidth Allocation (DWBA) in PONs

Dhaini et al. discussed in [36] that in an EPON, the dynamic wavelength and bandwidth allocation (DWBA) scheme grants an ONU over multiple wavelengths simultaneously, then it is possible that the later frames may finish transmission before earlier frames due to variable Ethernet frame lengths (64-1518 bytes). This increases the delay and buffer queue.

The transmission of any EPON ONU's upstream is a request-and-grant method. REPORT and GATE are the two Ethernet control messages that are used in DWBA scheme. An ONU sends the status of its queue to the OLT by the REPORT message. The OLT, after receiving the ONU status, grants the wavelength and time-slots to it according to their grant request.

Any DWBA is responsible for the assignment of wavelengths and time-slots. It is also responsible for the upstream transmission over single or multiple wavelengths. This assignment is a two-step procedure:

1. The grant size of the ONUs calculation.
2. Allocate over multiple wavelengths.

A. Dhaini rt al. propose an EPON-based DWBA algorithm with an assumption that the tuning speed of the ONUs are in the microsecond range. They have three different approaches of the scheme. According to their first version, the wavelength allocation is static, but the upstream bandwidth assignment is dynamic. Both the wavelength and bandwidth allocation. The second version of the scheme is the dynamic allocation of both the bandwidth and wavelengths. Their results show that the static wavelength allocation is disadvantageous when the traffic is high and the dynamic allocation improves the network efficiency [36].

Y. Luo et al. propose a DWBA algorithm for the TWDM-based PON where multiple XG-PONs are stacked [37]. Their results show that there is a deciding factor the load-balance and the tuning cost.

With the goal of solving scheduling methods for the transmissions over multiple wavelengths and how to reduce propagation delays in the long reach scenarios, Buttaboni et al. analyze the multi-thread polling in a long-reach PON and propose EFT-partial-VF Multi-threaded DWBA algorithm. Their results show improvement in the delays.

In [38], the authors proposed a dynamic bandwidth allocation (DBA) named Water-Filling or WF algorithm. In this scheme, the grant of an ONU is broken into smaller parts and spread in all the wavelengths. If all the channels have the same finish time for the last bandwidth assignment, this scheme would allocate those grant parts uniformly over all the available wavelengths. This would make all wavelengths busy and unavailable for the other ONUs. This leads to higher packet delays. These smaller parts of grants are not large enough that they can be transmitted over a wavelength. Thus, the queue of these frames has to wait the grant size on each channel is large enough to transmit to the destination. There is a possibility that the data frames need to wait for several allocation cycles to be transmitted. This situation increases the packet delay. As all the ONUs do the transmission over all the channels in the Water-Filling algorithm, every ONU faces the unordered frames issue.

The authors of [39] focus on the second stage of the procedure. Their proposed Single Channel As Possible Algorithm (SCAP-DWBA) is an offline-DWBA algorithm and it grants ONU on single wavelengths. This is how the ONUs get rid of frame reordering. Although the total bandwidth usage is exactly same as WF-DWBA, the proposed one offers less latency and reduced buffer occupancy.

They designed scheme collects all of the ONUs' grants and then decides their time-slot allocations. Following is the simple representation of this algorithm's steps:

1. Compute the total grant size of each ONU

2. For each ONU, check if the grant size is within the bandwidth limit.
3. Calculate the total grant size.
4. Sort the grants in descending order based on their grant sizes.
5. Find the wavelength with most available bandwidth.
6. If the first ONU grant size if less than or equal to the available bandwidth, then assign the grant. Otherwise, move to the next ONU.
7. After going through all of the ONUs as step 6, there may some ONUs left with unallocated grants.
8. Compute available bandwidth over all the wavelengths.
9. Check if the available bandwidth is equal or greater than the ONU grant or not. If yes, then assign and split the grant over the available wavelengths. Repeat this until no unassigned grant is left.

The authors have further optimization in the algorithm, named Single Channel As Possible + Grant Readjustment (SCAP+GR DWBA), by readjusting the frame reordering. The later wavelength's part of the grant is brought to the earliest time and the previous wavelength's grant portion remains the same (which is at the end of the wavelength). The authors created a discrete event simulator. They observed the average number of reordered frames and the average packet delay. They compare the three algorithms' results (SCAP, SCAP+GR, and WF). Their study shows the number of frame-reordered ONUs in SCAP DWBA is never more than three. In the most DWBA cycles, the SCAP+GR algorithm prevents the frame reordering situations. The rest are the cases where the grants of those ONUs are too large. The results of the packet delay show that WF algorithms has higher delay than the proposed two of the algorithms.

The proposed two algorithm assign grants on a single channel which leads to fewer guard times between grants.

Similar work is done by the authors of [40]. Their main goal is to ensure fair bandwidth distribution, lower latency, and avoid frame reordering. The proposed algorithm does not equalize all the wavelengths in a single bandwidth allocation instead transmission is done by using fewer number of wavelengths. This increases the bandwidth efficiency. Each ONU is assigned to one channel and all ONUs get grant in parallel which confirms the fairness. All the available wavelengths are sorted into ascending order of their start time and the grant is allocated in the wavelength with the earliest start time. Authors give comparison the average packet delay and the packet drop ratio for a specific size of buffer between the Water-Filling algorithm and their proposed scheme. Although the results show that the proposed scheme reduces packet drop rate and it does not increase the requirement for a larger buffer, this algorithm lacks explaining the situation when an ONU needs grant that requires more than one wavelength's bandwidth.

M. K. Multani et. al. proposed an algorithm, Partially Online Dynamic Bandwidth Allocation Algorithm (PAROND), which is designed for EPON in the hybrid TDM/WDM architecture [41]. This scheme has different ways to deal with the loads (high or low). After receiving REPORT messages from all ONUs, they are sorted based on their arrival time. This DWBA assigns grants to the highly loaded ONUs as soon as they request. This is done by the minimum requested bandwidth from HL ONUs and the excess bandwidth from the LL ONUs. As the HL ONUs are served right away, there would be less unserved heavy loaded ONUs in the system.

Another case would be when the requested bandwidth is larger than the minimum. In this situation, the OLT computes the total excess bandwidth from all ONUs and see if it satisfies the need. If it does not, then it waits for more excess bandwidth until it is equal to the requested amount. The results show that this algorithm reduces the average bandwidth wastage which means providing better bandwidth utilization. Although the average packet delay decreases over the low to medium loads, it remains the same for the highly loaded ONUs.

In this chapter, we discussed different types of DBA and DWBA schemes of PONs. We explain the proposed wavelength allocation schemes in the next chapter.

Chapter 3

Dynamic Wavelength Allocation Problem in NG-PON2

In the previous chapter, it has already been discussed that access-specific quality of service (QoS) in NG-PON2 systems depends on the allocation of the available resources. A dynamic bandwidth allocation (DBA) scheme allows the system to add more subscribers to the access network and to support enhanced services. It is a method of assigning bandwidth to the ONUs based on their traffic contracts and the usage patterns. The standard for NG-PON2 (ITU-T G.989) describes the bandwidth allocation in a single wavelength, but it leaves the wavelength allocation issue to the implementers' preferences as long as the base cases, which are discussed in the standard specification, are handled [5].

In this chapter, the focus is on the wavelength assignment part, assuming that the system applies conventional DBA method described in the standard G.989. It is also assumed that the same DBA is used for every wavelength. In the previous chapter, we discuss that any DWBA is a two-step procedure: the grant size based on the each ONU's request and allocating that over single/multiple wavelengths. The OLT and ONUs exchange messages (Request and Grant). Based on each ONU's Request message, the OLT evaluates the upstream bandwidth allocation. Then it sends the allocated grant information to each ONU through a Grant message. The ONUs start transmission based on the grant.

The initial objective of this study is to minimize the total day of the high priority data. To fulfill the purpose, five methods of wavelength allocation are proposed. The proposed first method, No Block-Split, assigns a grant in a single channel. Contrarily, next proposed scheme, Equal Block-Split, splits a grant equally and transmits over all the wavelengths. Then, different priority-class is introduced. The third and fourth methods (Priority-based No Block-Split & Priority-based Equal Block-Split) sort the grants based on their priority classes and then assign them in single or multiple wave- lengths, respectively. Finally, the fifth, Priority-based Decider Block-Split scheme, is a hybrid of both the third and fourth approaches. Based on the priority class and data size, it decides whether a grant should be transmitted over single or multiple wavelengths.

The rest of this chapter is organized as follows. Section 3.1 describes the five proposed methods with examples of different scenarios. Section 3.2 gives the mathematical model of the problem and section 3.3 explains heuristics.

3.1 Proposed Methods

3.1.1 No-Split Method

The OLT assigns grants to each request in a single channel if this method is applied in the system. Each grant is assigned in the wavelength which has the earliest available time.

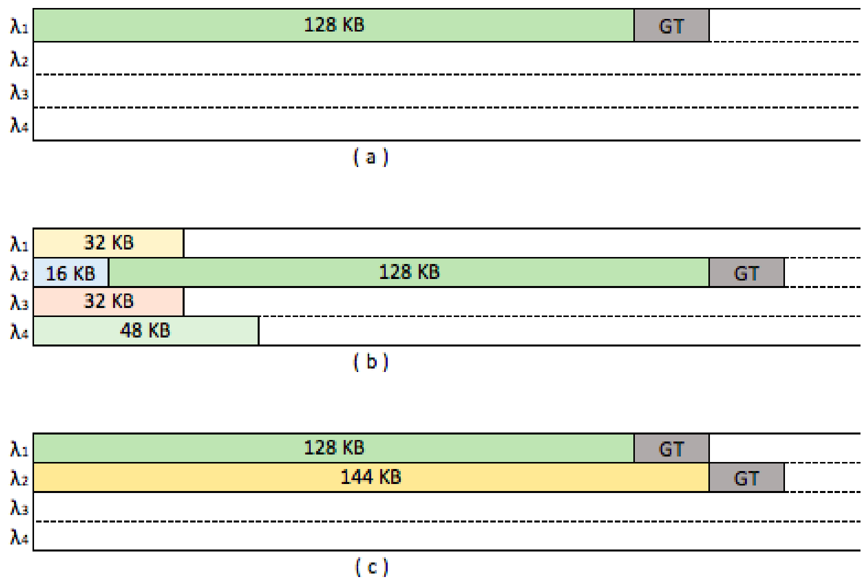

Figure 3.1: No Block-Split

The above figure explains different cases of the No Block-Split scheme assignment. Suppose that a 128 KB grant is requested by an ONU. According to this algorithm, it would assign the entire grant on the first available wavelength, λ_1 as in Fig. 3.3.2(a). If these wavelengths are not available on the exact time,as in Fig. 3.3.2(b), No Block-Split scheme would assign grant of 128 KB on the unoccupied wavelength with the earliest available time, λ_2. The third case, Fig. 3.3.2(c), shows that the new grant would always select the unoccupied wavelength. The new grant 144 KB is assigned to the wavelength λ_2. It is to ensure that different grants can transmit simultaneously without interfering with one another.

3.1.2 Equal-Split Method

The OLT splits the grants in equal sizes and transmit those parts through all the channels. If a grant size if S and the number of active wavelength is m, then each wavelength would carry $\frac{S}{m}$ amount of the grant.

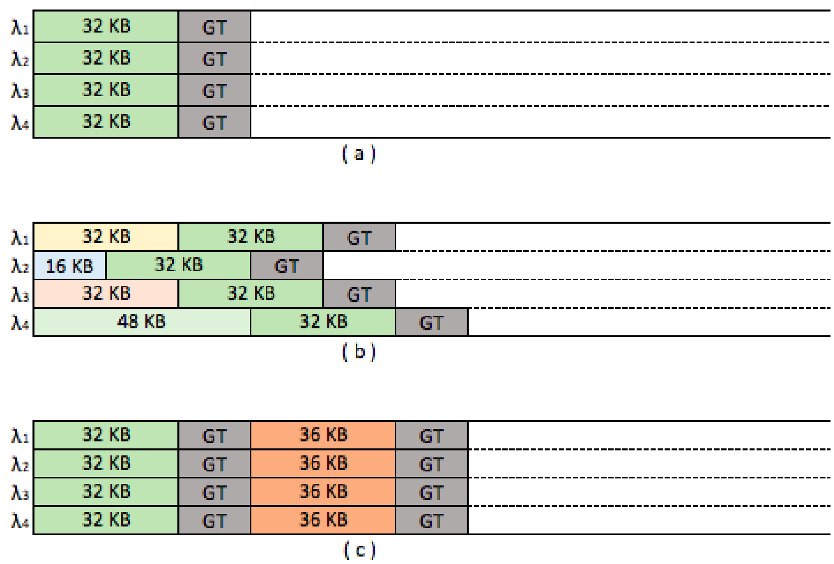

Figure 3.2: Equal Block-Split

The above figure explains different cases of the Equal Block-Split scheme assignment. Suppose that a request of 128 KB grant is reported by an ONU. According to this algorithm, it would split the entire grant into equal four parts and then transmit over all the wavelengths as in Fig. 3.2(a). If these wavelengths are not available on the exact time, as in Fig. 3.2(b), EBH would assign grant of 32 KB on a wavelength as soon as they become available. Thus, the grant assignment for Fig. 3.2(b)'s example would on λ_2 first, then λ_3, λ_1, and finally λ_4. The third case, Fig. 3.2(c) shows that the new grant would be transmitted after the first one finishes. The new grant 144 KB's transmission start time would be 32 KB + guard time at each wavelength. It is to ensure that different grants can transmit simultaneously without interfering with each other. The Equal Block-Split system would have four times guard time than No Block-Split.

3.1.3 Priority Classes

The next three methods that are proposed in this work, deal with the priority of both the data and customer type. Two main classes of the priority are introduced in this work: Customer and Traffic. The customer base priority-levels are business customer and residential users. There classes are A and B, respectively. Based on the traffic type, there are three types:

(1) Live: Live telecasting, interactive online game, VoIP calls.

(2) Video: TV shows, other video services (e.g. YouTube, Netflix, etc.).

(3) Data: services like browsing, email, etc.

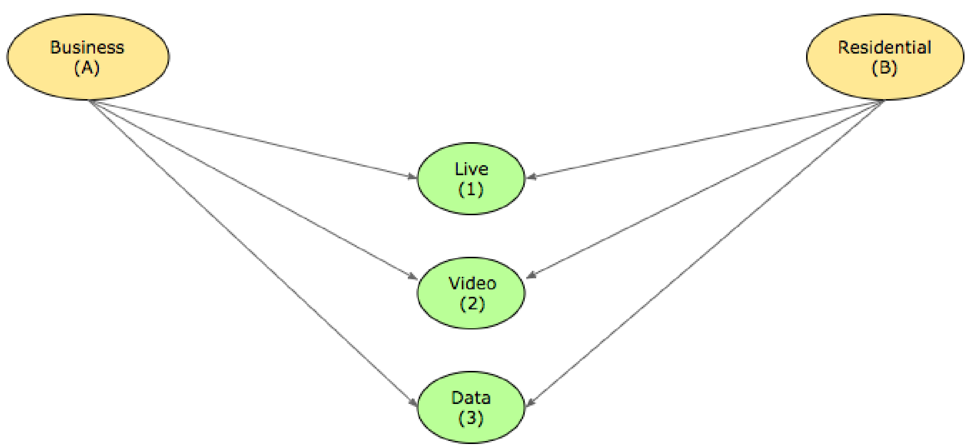

Figure 3.3: Priority Class Combinations

Fig. 3.3 depicts that each customer level uses three types of traffic types. Considering these two types of customer classes, six combinations are possible. Each of these combinations has a weight. The weight range is 1 to 6 whereas 1 represents the highest priority and 6 has the lowest.

Table 3.1: Priority Class Combinations

Customer Base	Service Type	Priority Class	Priority Weight
Business	Live	A1	1
Residential	Live	B1	2
Business	Video	A2	3
Residential	Video	B2	4
Business	Data	A3	5
Residential	Data	B3	6

The business users have higher priority over the residential users. The "live" category service is extremely delay sensitive. Thus, it has the highest priority than the data service (email, browse, etc). Table 3.1 explains all these six combinations with their class and priority weight. The classes A1, B1, A2, B2 include live telecasting, video, teleconferences, etc. These need parallel data transmission of minimize the delay. On the other hand, A3 and B3 types are delay-tolerant. They do not need to send over multiple wavelengths which lead to bandwidth wastage.

3.1.4 Priority Based No-Split Method

The OLT sorts all the grants based on their priority weights. The grants with priority weight 0 are transmitted first. By this way the grants are sent one-by-one. Each grant is transmitted through one single channel. Each grant is assigned in the wavelength which has the the earliest available time.

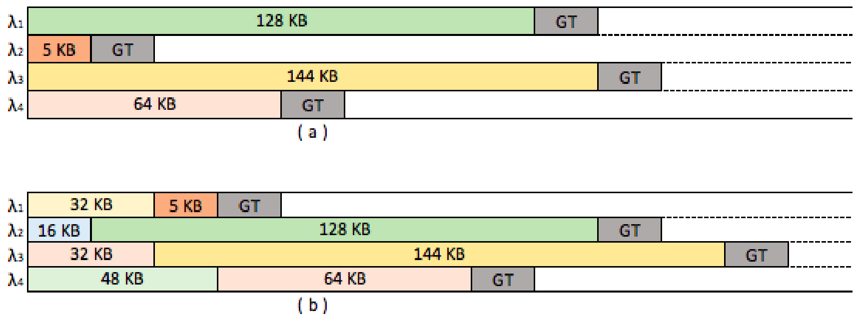

Figure 3.4: Priority-Based No Block-Split

The Fig. 3.3.3 explains different cases of the No Block-Split assignment. Suppose that there are four requests (64 KB, 144 KB, 5 KB, and 128 KB) are reported by four ONUs with the priority classes of $A3, B2, B1, A1$, respectively. This scheme would sort the grants according to the priority classes. Then it would assign the entire grant on the first available wavelength one-by-one as in Fig. 3.3.3(a). If these wavelengths are not available on the exact time, as in Fig. 3.3.3(b), Priority-Based No Block-Split scheme would assign wavelength to the grant with the highest priority (128 KB) on the unoccupied wavelength with the earliest available time, λ_2.

3.1.5 Priority Based Equal-Split Method

The OLT sorts all the grants based on their priority weights. The grants with priority weight 0 are transmitted first. The rest of the data transferring procedure is same as the Equal Block-Split system: the grants are split equally and send through all the wavelengths.

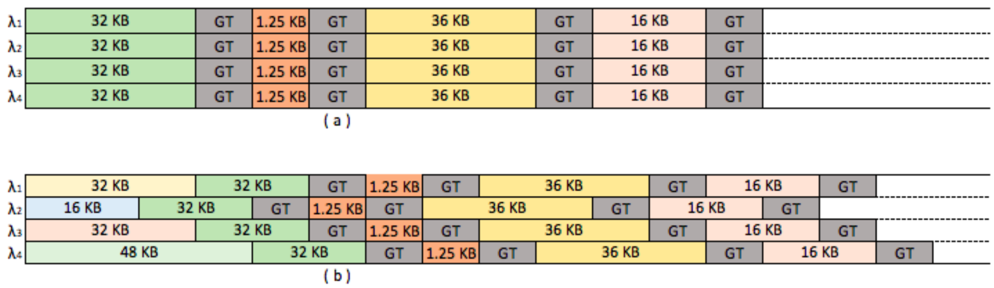

Figure 3.5: Priority-Based Equal Block-Split

The Fig. 3.3.4 explains different cases of the Priority-Based Equal Block-Split assignment. Suppose that there are four requests (32 KB, 120 KB, 5 KB, and 64 KB) are reported by four ONUs with $A3, B2, B1, A1$, respectively. This scheme would first sort the grants according to the priority levels. According to this algorithm, it would split the entire grant into four parts and then transmit over all the wavelengths as in Fig. 3.3.4(a). If these wavelengths are not available on the exact time, as in Fig. 3.3.4(b), Priority-Based Equal Block-Split would start assigning the 16 KB of the 64 KB grant on a wavelength as soon as they become available. Thus, the grant assignment for 64 KB would be on λ_2 first, then λ_3, λ_1, and finally λ_4. After this transmission, the system starts transmitting the split parts one-by-one.

3.1.6 Priority Based Decider-Split Method

The OLT sorts all the grants based on their priority weights. Unlike the previous two methods, this scheme does not transmit grants only over one or all wavelengths. It transmits the high priority grants (class A1, B1, A2, B2) exactly like the Priority-Based Equal Block-Split methods. Each of the low priority grant (A3 and B3) is sent over one single channel.

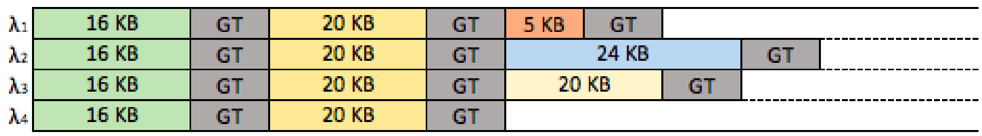

Figure 3.6: Priority-Based Decider Block-Split

Suppose there are five requests at the OLT (24 KB, 5 KB, 20 KB, 64 KB and 80 KB) are reported by four ONUs with the priority classes of $A3, A2, B3, B1$, and $A1$, respectively. The Priority-Based Decider Block-Split scheme would first sort the grants according to the priority levels: 64 KB, 80 KB, 5 KB, 24 KB, 20 KB. Then grants would be transmitted based on their priority weights. The A1, B1, A2, B2 classed requests would be split over all the wavelengths as in Fig. 3.6. Although 5 KB belongs to A2 class, it would not be split as the size is too small. Splitting would waste four times of guard band. The rest of the grants would be transmitted by using single channel. This confirms the highest priority data's faster transmission, reduced bandwidth wastage by not splitting the lower priority and/small sized data requests.

3.2 Mathematical Formulation

To solve the wavelength assignment problem with the goal of minimizing the total transmission delay of high priority data, we construct a Mixed Integer Linear Programming (MILP) model with the integer constraints to obtain the optimal solutions. The formulations can be solved with IBM CPLEX optimization software [42], from which an optimal solution is reached.

MILP formulations are developed to complete the wavelength allocation for all the requests. Two types of inputs are offered for the MILP formulations.

Firstly, the total number of wavelengths, and the available bandwidth in each of those channels. Secondly, the requests from ONUs and their arrival times to the OLT. In the following section, we discuss the inputs, the constraints, and the related parameters in the MILP formulations.

3.2.1 Model Inputs

In the network model, we have OLT and ONUs. Each ONU operates in four or eight wavelengths in an NG-PON2 system. The wavelengths can be defined as: $w_j = (t_s, t_{d_i}, d_r)$. The variable t_s is the available time of the wavelength w_j, t_d is its duration of availability for a grant G_i, d_r is the data rate. We define the set of all requests and denote each element as R_i. Every request has a arrival time A_i, a transmission start time S_{ij} at wavelength w_j.

It also has end time E_i and a priority p.

The detailed parameter information for the inputs described above are listed in the following. In addition, we also list other related variables that are used in the MILP formulations.

Input Parameters:

N: Total number of requests

R_i: The requested grant for ith request

A_i: The arrival time of the ith request

d_r: The data rate of each wavelength

B_{aT}: The total available bandwidth

B_{aj}: The total available bandwidth in wavelength w_j

p_i: The priority of the ith grant

n: an integer value

K: Large positive value

Constant Parameters:

M: Total number of wavelengths

W: Set of wavelengths $\{w_1, w_2, .., w_M\}$

t_g: The guard-band between two transmission slots

Variables:

G_{ij}: The ith grant on w_j

G: The total grant

S_{ij}: Start time of the ith grant on w_j

E_i: End time of the ith grant

E_{ij}: End time of the ith grant's portion at wavelength w_j

x_{ij}: Binary parameter, equals 1 when ith grant uses wavelength w_j

b_{G_i}: Binary parameter, equals 1 if a grant G_i is scheduled for transmission

$\overline{b_{G_i}}$: 1 - b_{G_i}

3.2.2 Objective and Constraints

No-split and Equal-Split Methods: The objective is to reduce the total time duration between a request's arrival time to transmission finish time.

Priority Based No-split, Equal-Split, and Decider-Split Methods: The objective is to reduce the total time duration between the higher priority request's arrival time to transmission finish time. This means that the higher priority request should be transmitted before the lower priority ones.

Objective:

$$\textit{minimize:} \sum_{i=1}^{N}(E_i - A_i) + \sum_{i=1}^{N} K^{p_i}$$

Here, the value of p would always be 0 for the NBH and EBH methods.

Subject to:

$$\sum_{i=1}^{N}\sum_{j=1}^{M} G_{ij} \leq B_{aT}, \forall i \in N, \forall j \in M \tag{3.1}$$

$$\sum_{j=1}^{M} G_{ij} \geq R_i, \forall i \in N, \forall j \in M \tag{3.2}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M} G_{ij} \geq G, \forall i \in N, \forall j \in M \tag{3.3}$$

$$\sum_{j=1}^{M} B_{aj} \leq B_{aT}, \forall j \in M \tag{3.4}$$

$$S_{ij} \geq A_i, \forall i \in N \tag{3.5}$$

$$\sum_{i=1}^{N} b_{G_i} - \sum_{i=1}^{N}\sum_{j=1}^{M} x_{ij} = 0, \forall i \in N, \forall j \in M \tag{3.6}$$

$$\sum_{j=1}^{M} E_{ij} \geq E_i, \forall i \in N, \forall j \in M \tag{3.7}$$

$$\sum_{j=1}^{M}[E_{ij} - S_{ij}] \geq G_i, \forall i \in N, \forall j \in M \tag{3.8}$$

$$S_{(i+1)j} - S_{ij} \leq x_{ij} * (d_r + t_g), \forall i \in N, \forall j \in M \tag{3.9}$$

$$b_{G_i} \geq x_{ij}, \forall i \in N, \forall j \in M \tag{3.10}$$

$$x_{ij} \leq 1, \forall i \in N, \forall j \in M \tag{3.11}$$

$$x_{ij} \in \{0, 1\}, \forall i \in N, \forall j \in M \tag{3.12}$$

$$b_{G_i} \in \{0, 1\}, \forall i \in N, \forall j \in M \tag{3.13}$$

$$\sum_{i=1}^{N} b_{G_i} \leq n, \forall i \in N \tag{3.14}$$

$$n \in \mathbb{Z}^+ \tag{3.15}$$

We define these following constraints:

- Constraint (3.1) guarantees that the sum of all assigned grants do not exceed the total available bandwidth of the system.

- Constraint (3.2) ensures that the sum of the *ith* grant on all wavelengths should be equal to the size of the *ith* request.
- Constraint (3.3) maintains that the sum of all the grants on all wavelengths should be equal to the total grant.
- Constraint (3.4) assures that the available bandwidth remains equal to the sum of all wavelengths' available bandwidth.
- Constraint (3.5) ensures that the *ith* request's transmission start time at wavelength w_j should not be earlier that its arrival time.
- Constraint (3.6) secures that the sum of all the *ith* grant using wavelength w_j should be equal to the number of transmission of that grant.
- Constraint (3.7) ensures that the sum of the end times of all the portions of a grant is within the limit of the total end time. In NBH and P-NBH systems, only one wavelength would be used to transmit. Thus, end times over the rest of the wavelengths would always be 0.
- Constraint (3.8) is used to make sure that the sum of all $E_{ij} - S_{ij}$ is equal to the total grant size of that request.
- Constraint (3.9) confirms that two consecutive transmission windows do not overlap.
- Constraint (3.10) is used to ensure whether a request is scheduled for transmission or not.
- Constraint (3.11) ensures that a wavelength is chosen at most one for each request.
- Constraint (3.12) and (3.13) form x_{ij} and b_{G_i} as binary variables.

- Constraint (3.14) guarantees that no request is sent twice and (3.15) maintains n as a positive integer.

The priority classes have weights from 1 to 6 respectively. This means the highest priority class A1 has a priority weight of 1 and the lowest priority class B3 has a priority weight of 6. The objective function would obtain a higher value when low priority grants are favored over the high ones because K is raised to a power to the weight of the request's priority.

3.3 Heuristics for Dynamic Wavelength Allocation Problem

The formulations discussed in the previous section can be solved with IBM CPLEX optimization software [42], but the executing time is too long to get allocation results within one scheduling cycle. The wavelength allocation problem is a NP-hard [43] problem. The optimal solution-ed algorithm would have very high complexity. Thus, we propose five heuristic wavelength allocation algorithms of low complexity which are implementable to get near-optimal solutions of the allocation problem.

The heuristics have some assumptions:

- The buffer size at the ONUs and the OLT are both infinite.
- All ONUs are always at a uniform distance from the OLT.
- All the wavelengths' available times are always set to the same at the beginning of the transmission.

Our five time-efficient heuristic algorithms are: No Block-Split Heuristic, Equal Block-Split Heuristic, Priority Based No Block-Split Heuristic, Priority Based Equal Block-Split Heuristic, and Priority Based Decider Block-Split Heuristic. These methods are explained in the sections 3.3.2 to 3.3.5.

3.3.1 No Block-Split Heuristic (NBH)

The No Block-Split Heuristic (NBH) is a greedy algorithm. The basic idea of NBH algorithm is to assign each of the grants over one single channel. In addition, it assigns to the the wavelength which is earliest available among all four. Based on these ideas, the NBH algorithm comprises of two main steps: after checking if there is enough unoccupied bandwidth in the available wavelength, the allocation takes place.

As in this scheme a grant is assigned only in one single channel, the NG-PON2 architecture eliminates the possibility of frame-reordering problem at the ONU and uses minimum number guard bands compared to EBH. Also, instead using all wavelength for a single grant, this scheme allows the system to keep other channels unoccupied for the next request allocation.

The No Block-Split Heuristic (NBH) is shown in Algorithm 1. In the line 3 of the algorithm, the OLT checks if each of the requests is within the allowed bandwidth limit, $maxB_i$, where i is the index of the request. This allowed bandwidth depends on the user's agreement with their service provider. This has the time complexity of $O(N)$. The sorting of the available wavelength takes $Mlog(M)$. Line 6-9 is the part that has the time complexity of $O(MN)$. Therefore, the total time complexity of No Block-Split Heuristic is $O(N + Mlog(M) + MN)$.

Algorithm 1 No Block-Split Heuristic (NBH)

Input and Initialization:
M; //Number of total wavelengths
N; //Total number of ONUs
$W = \{w_1, w_2, ..., w_M\}$; //Set of wavelengths, sorted in ascending manner according to their start time
B_{a_T}; //Total available bandwidth
B_{a_j}; //Available bandwidth at wavelength w_j
$maxB_i$; //Maximum allowed grant for ith ONU
$R = \{R_1, R_2, ..., R_N\}$; //Set of requests from all ONUs
$G = \{G_1, G_2, ..., G_N\}$; //Set of grants for all ONUs
$G_T \leftarrow 0$; //Total bandwidth grant is initialized to 0

Update current available resources in the network;
OLT collects all the requests from all ONUs;
for all $R_i \in R$ **do**
    $G_i = min\{R_i, maxB_i\}$
Sort wavelengths in ascending order (W) according to their earliest available time;
for all $G_i \in G$ **do**
    for all $w_j \in W$ **do**
        if $G_i \leq B_{a_j}$
            Assign G_i to w_j and **exit**

3.3.2 Equal Block-Split Heuristic (EBH)

The basic idea of the Equal Block-Split Heuristic (EBH) algorithm is to split the grant into equal four parts and then assign those over all the four wavelengths. In addition, it does not care about the earliest available wavelengths. Based on these ideas the EBH algorithm comprises of two main steps: after splitting the grant into equal four parts, the allocation takes place over all the wavelengths.

As in this scheme a grant is assigned over all the wavelengths, it equalizes the wavelength usage most of the times. This scheme allows to transmit data in one-fourth time duration than the single wavelength assignment system, but uses four-times more guard-bands.

Algorithm 2 Equal Block-Split Heuristic (EBH)

Input and Initialization:
M; //Number of total wavelengths
N; //Total number of ONUs
$W = \{w_1, w_2, ..., w_M\}$; //Set of wavelengths, sorted in ascending manner according to their start time
B_{a_T}; //Total available bandwidth
B_{a_j}; //Available bandwidth at wavelength w_j
$maxB_i$; //Maximum allowed grant for ith ONU
$R = \{R_1, R_2, ..., R_N\}$; //Set of requests from all ONUs
$G = \{G_1, G_2, ..., G_N\}$; //Set of grants for all ONUs
$G_T \leftarrow 0$; //Total bandwidth grant is initialized to 0

- -

```
1: Update current available resources in the network;
2: OLT collects all the requests from all ONUs;
3: for all R_i ∈ R do
4:    G_i = min{R_i, maxB_i}
5: Sort wavelengths in ascending order (W) according
       to their earliest available time;
6: for all G_i ∈ G do
7:    if G_i ≤ B_{a_T}
8:       Assign G_i to all W by splitting them equally and exit
```

The Equal Block-Split Heuristic (EBH) is shown in Algorithm 2. In the line 3 of the algorithm, the OLT checks if each of the requests is within the allowed bandwidth limit, $maxB_i$, where i is the index of the requests. This allowed bandwidth depends on the user's agreement with their service provider. This has the time complexity of $O(N)$. The sorting of the available wavelength takes $Mlog(M)$. Line 6-8 is the part that has the time complexity of $O(N)$. Therefore, the total time complexity of Equal Block-Split Heuristic is $O(N+Mlog(M)+N)$ or $O(2N + Mlog(M))$.

3.3.3 Priority Based No Block-Split Heuristic (P-NBH)

The Priority-Based No Block-Split Heuristic (P-NBH) is a greedy algorithm. The basic idea of P-NBH algorithm is same as the NBH: to assign each of the grants over one single channel. In addition, before assigning, the grants are sorted according to their priority classes. Based on these ideas, the NBH algorithm comprises of three main steps: the sorting of the grants, then after checking if there is enough unoccupied bandwidth in the available wavelength, the allocation occurs.

As this scheme also assigns a grant only in one single channel, the NG-PON2 architecture eliminates the possibility of frame-reordering problem at the ONU. The high priority grants get the chance to be transmitted before than lower ones. Also, instead using all wavelength for a single grant, this scheme allows the system to keep other channels unoccupied for the next request allocation.

The Priority-Based No Block-Split Heuristic (P-NBH) is shown in Algorithm 3. In the line 3 of the algorithm, the OLT checks if each of the requests is within the allowed bandwidth limit, $maxB_i$, where i is the index of the requests. This allowed bandwidth depends on the user's agreement with their service provider. This has the time complexity of $O(N)$. The time complexity of the sorting of the priority and the available wavelength takes $Nlog(N)$ and $Mlog(M)$, respectively. Line 7-10 is the part that has the time complexity of $O(MN)$. Therefore, the total time complexity of Priority-Based No Block-Split Heuristic is $O(N + Nlog(N) + Mlog(M) + MN)$.

Algorithm 3 Priority-Based No Block-Split Heuristic (P-NBH)

Input and Initialization:
M; //Number of total wavelengths
N; //Total number of ONUs
$W = \{w_1, w_2, ..., w_M\}$; //Set of wavelengths, sorted in ascending manner according to their start time
B_{a_T}; //Total available bandwidth
B_{a_j}; //Available bandwidth at wavelength w_j
$maxB_i$; //Maximum allowed grant for ith ONU
$R = \{R_1, R_2, ..., R_N\}$; //Set of requests from all ONUs
$G = \{G_1, G_2, ..., G_N\}$; //Set of grants for all ONUs
$G_T \leftarrow 0$; //Total bandwidth grant is initialized to 0
$P_G = \{P_{G_1}, P_{G_2}, ..., P_{G_N}\}$; //Set of sorted grants based on their priority (high-to-low) for all ONUs
$P = \{A1, B1, A2, B2, A3, B3\}$; //Set of sorted priorities from high-to-low

- -

```
Update current available resources in the network;
OLT collects all the requests from all ONUs;
for all R_i ∈ R do
   G_i = min{R_i, maxB_i}
Sort G based on their priorities: from high to low (P_G);
Sort wavelengths in ascending order (W) according
      to their earliest available time;
for all G_i ∈ G do
   for all w_j ∈ W do
      if G_i ≤ B_{a_j}
         Assign G_i to w_j and exit
```

3.3.4 Priority Based Equal Block-Split Heuristic (P-EBH)

The basic idea of the Priority-Based Equal Block-Split Heuristic (P-EBH) algorithm is same as EBH algorithm which is to split the grant into equal four parts and then assign those over all the four wavelengths. In addition, before assigning, the grants are sorted according to their priority classes. Based on these ideas, the P-EBH algorithm comprises of three main steps: the sorting of the grants, then after splitting the grant into equal four parts, the allocation takes place over all the wavelengths.

As in this scheme a grant is assigned over all the wavelengths, it equalizes the wavelength usage most of the times. This scheme allows to transmit data in one-fourth time duration than the single wavelength assignment system, but like EBH, it too uses four-times more guard-bands.

Algorithm 4 Priority-Based Equal Block-Split Heuristic (P-EBH)

Input and Initialization:
M; //Number of total wavelengths
N; //Total number of ONUs
$W = \{w_1, w_2, ..., w_M\}$; //Set of wavelengths, sorted in ascending manner according to their start time
B_{a_T}; //Total available bandwidth
B_{a_j}; //Available bandwidth at wavelength w_j
$maxB_i$; //Maximum allowed grant for ith ONU
$R = \{R_1, R_2, ..., R_N\}$; //Set of requests from all ONUs
$G = \{G_1, G_2, ..., G_N\}$; //Set of grants for all ONUs
$G_T \leftarrow 0$; //Total bandwidth grant is initialized to 0
$P_G = \{P_{G_1}, P_{G_2}, ..., P_{G_N}\}$; //Set of sorted grants based on their priority (high-to-low) for all ONUs
$P = \{A1, B1, A2, B2, A3, B3\}$; //Set of sorted priorities from high-to-low

- -

1: Update current available resources in the network;
2: OLT collects all the requests from all ONUs;
3: **for all** $R_i \in R$ **do**
4:     $G_i = min\{R_i, maxB_i\}$
5: Sort G based on their priorities: from high to low (P_G);
6: Sort wavelengths in ascending order (W) according to their earliest available time;
7: **for all** $G_i \in G$ **do**
8:     **if** $G_i \leq B_{a_T}$
9:         Assign G_i to all W by splitting them equally and **exit**

The Priority-Based Equal Block-Split Heuristic (P-EBH) is shown in Algorithm 4. In the line 3 of the algorithm,, the OLT checks if each of the requests is within the allowed bandwidth limit, $maxB_i$, where i is the index of the ONUs. This allowed bandwidth depends on the user's agreement with their service provider. This has the time complexity of $O(N)$. The time complexity of the sorting of the priority and the available wavelength takes $Nlog(N)$ and $Mlog(M)$, respectively. Line 7-9 is the part that has the time complexity of $O(N)$. Therefore, the total time complexity of Priority-Based Equal Block-Split Heuristic is $O(N+Nlog(N)+Mlog(M)+N)$ or $O(2N+Nlog(N)+Mlog(M))$.

3.3.5 Priority Based Decider Block-Split Heuristic (P-DBH)

We propose another version of wavelength assignment algorithm, The Priority-Based Decider Block-Split Heuristic (P-DBH), which offers data splitting for faster transmission to the high priority data and single channel assignment to the data with small sizes or with low priority. This algorithm is a combination of P-NBH and P-EBH.

The Priority-Based Decider Block-Split Heuristic (P-DBH) is shown in Algorithm 5. In the line 3 of the algorithm, the OLT checks if each of the requests is within the allowed bandwidth limit, $maxB_i$, where i is the index of the requests. This allowed bandwidth depends on the user's agreement with their service provider. This has the time complexity of $O(N)$. The time complexity of the sorting of the priority and the available wavelength takes $Nlog(N)$ and $Mlog(M)$, respectively. Line 7-19 have two nested loops: one at line 7 and another at line 9. The time complexity is $O(NM)$. Therefore, the total time complexity of Priority-Based Decider Block-Split Heuristic is $O(N + Nlog(N) + Mlog(M) + MN)$.

Algorithm 5 Priority-Based Decider Block-Split Heuristic (P-DBH)

Input and Initialization:
M; //Number of total wavelengths
N; //Total number of ONUs
$W = \{w_1, w_2, ..., w_M\}$; //Set of wavelengths, sorted in ascending manner according to their start time
B_{a_T}; //Total available bandwidth
B_{a_j}; //Available bandwidth at wavelength w_j
$maxB_i$; //Maximum allowed grant for ith ONU
$R = \{R_1, R_2, ..., R_N\}$; //Set of requests from all ONUs
$G = \{G_1, G_2, ..., G_N\}$; //Set of grants for all ONUs
$G_T \leftarrow 0$; //Total bandwidth grant is initialized to 0
$P_G = \{P_{G_1}, P_{G_2}, ..., P_{G_N}\}$; //Set of sorted grants based on their priority (high-to-low) for all ONUs
$P = \{A1, B1, A2, B2, A3, B3\}$; //Set of sorted priorities from high-to-low
d_{low}; // Minimum grant-size that is allowed for multiple wavelength assignment

---

Update current available resources in the network;
OLT collects all the requests from all ONUs;
for all $R_i \in R$ **do**
  $G_i = min\{R_i, maxB_i\}$
Sort G based on their priorities: from high to low (P_G)
Sort wavelengths in ascending order (W) according to their earliest available time;
for all $P_{G_i} \in P$ **do**
  if $P_{G_i} \leq B_{a_T}$
    for all $w_j \in W$ **do**
      if $P_{G_i} > B_{a_j}$
        Assign P_{G_i} to all W by splitting them equally
      if $P_{G_i} \leq B_{a_j}$
        if $P_{G_i} \leq d_{low}$
          Assign P_{G_i} to w_j
        if $P_{G_i} > d_{low}$
          if P_{G_i}'s priority category is A1 or B1
            Assign P_{G_i} to all W by splitting them equally
          else
            Assign P_{G_i} to w_j

Chapter 4

Experimental Results & Analysis

The performance evaluation of our proposed schemes are done by examining two cases. First, we compare the static mathematical model with the heuristic cases. Second, we simulate the five proposed heuristic algorithms, and analyze different parameters.

In both the cases, we iterate 100 independent instances to confirm that all the values in the plots have a 95% confidence interval.

4.1 MILP versus Heuristic

The mathematical model discussed in the previous chapter is converted into AMPL language. AMPL (A Mathematical Programming Language) is an algebraic modeling language. This is used to illustrate and solve the problems with high-complexity [44].

We input our problem into AMPL and then it uses a solver to come up with an optimal solution. The solver that we use is CPLEX [42]. But, this whole process takes a huge amount of time and it increases with the size of input. In our experiment, it takes more than two hours to solve the optimal resource allocation for a eight requests experiment in 32-ONU system. Therefore, we only use the proposed heuristic schemes to conduct the experiments for this system.

To evaluate the performances of the five proposed heuristic algorithms, a MATLAB simulation system is built. We simulate a NG-PON2 system with 4 wavelengths. Each of these wavelengths support 10 Gbps in both the upstream and downstream transmission. We simulate the system which consist of 32 ONUs and they all are at a distance of 40 km from the OLT. The number of wavelengths available to the OLT is 4 with a line rate of 10 Gbps each. The average data-rate for each ONU is 4*10 Gbs/32 or 1.25 Gbps. The guard band is 3 KB. We generated requests with random sizes. For the simulation, we assumed the 35% of the requests belong to A1 & B1 priority classes and the remaining 65% requests belong to the other priority classes.

We have some assumptions for the simulations purpose:

- The buffer size at the ONUs and the OLT are both infinite.
- All the requests are within the limit of the grant size which means $R_i = G_i \forall i$
- All ONUs are at a distance of 40 km from the OLT.
- The guard band size is 3 KB.
- All ONUs support four wavelengths.
- Four of the wavelengths' available time are set to the same at the beginning of the simulation.

The optimal solutions for wavelength allocation problem can be found by solving the MILP formulations with the CPLEX Optimization software, but the process is highly time consuming. In our experiment, it takes hours to solve the optimal resource allocation for only for 8 requests in the system with 32 ONUs.

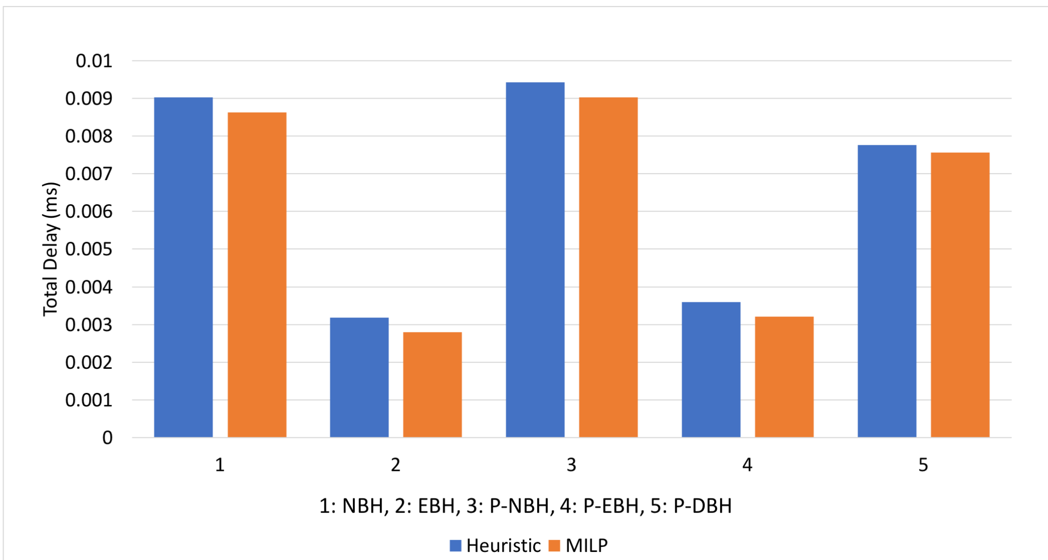

Figure 4.1: Total delay of five DWBA schemes

When given eight requests, the heuristic can provide the near optimal solution compared to CPLEX. The execution time of heuristic approach is near to a few microseconds. When given more requests, the results from the CPLEX method converges slower than the heuristic method. Thus, larger numbers of requests are only tested by the heuristic methods in the later experiments.

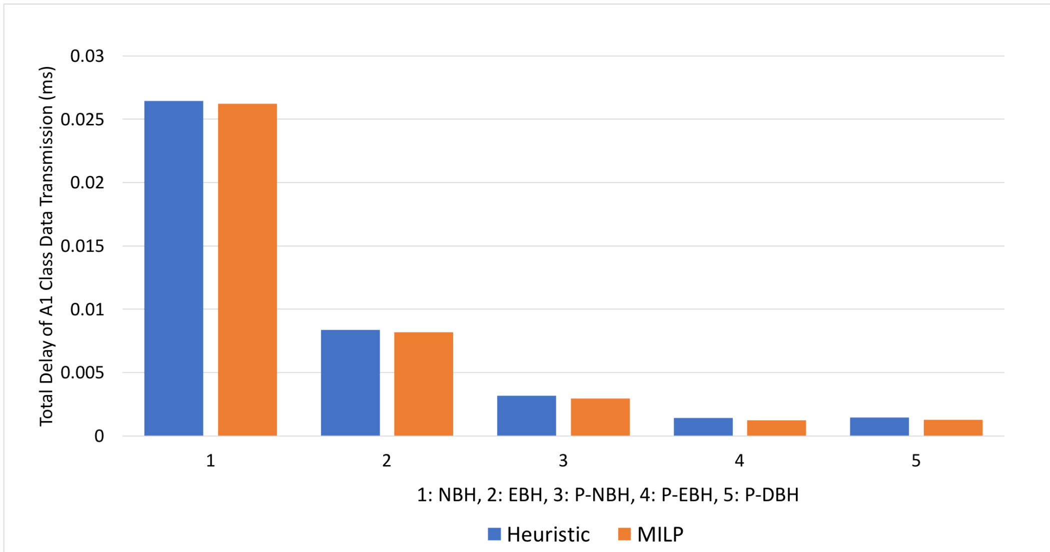

Figure 4.2: Total Delay of A1 Class Data Transmission

In Fig. 4.1, we see that the results of the total delay from MILP and the heuristic shows that the heuristic algorithms perform almost the same as MILP. The heuristics have 7.49% more delay than the MILP on average.

Similarly, in Fig. 4.2 the total transmission delay of the A1 class data from MILP and the heuristic shows that the heuristic algorithms perform almost the same as MILP. The heuristics have 8.24% more delay than the MILP on average.

4.2 Single versus Multiple Wavelength Allocation

In each run, 100 - 200 requests are generated from 32 ONUs. For the purpose of validity, we run the algorithms 100 times to observe and compare the results.

4.2.1 Bandwidth Usage

Fig. 4.3 shows that the NBH uses less bandwidth than EBH and the usage continues to increase with the number of requests. This can be explained by the fact that the later one uses 4 times more guard-bands than the other. This comparison indicates that the NBH is much more bandwidth efficient than EBH.

From this extra usage shown in Fig.4.3, we can use this data to find the percentage of bandwidth wastage. The following formula is used to find the wastage percentage by EBH over NBH.

$$\frac{BW_{EBH} - BW_{NBH}}{BW_{NBH}} * 100\%$$

Figure 4.4 depicts the percentage of bandwidth wastage by EBH over NBH. This plot shows the relationship between the bandwidth wastage and the number of requests.

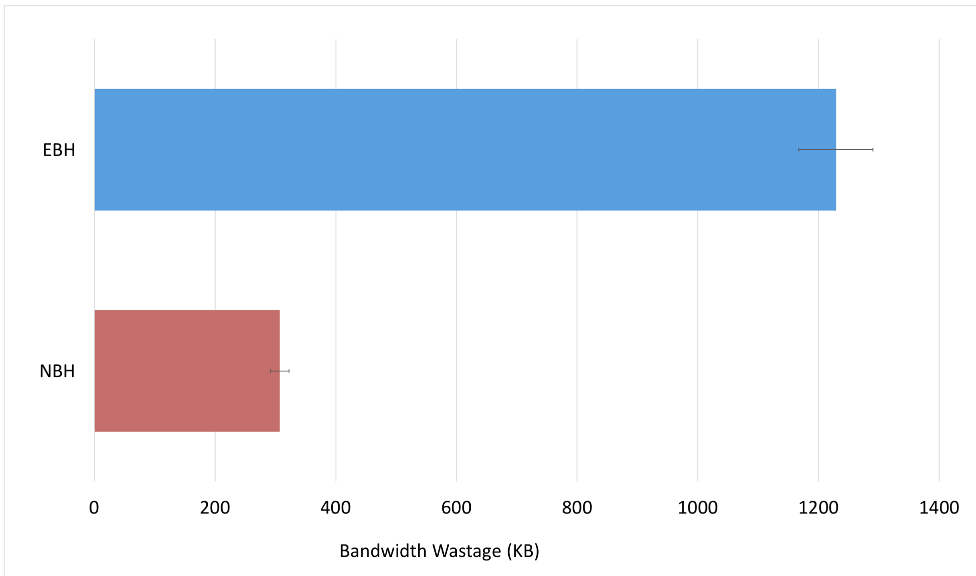

Figure 4.3: Extra bandwidth used EBH than NBH due to the guard-bands

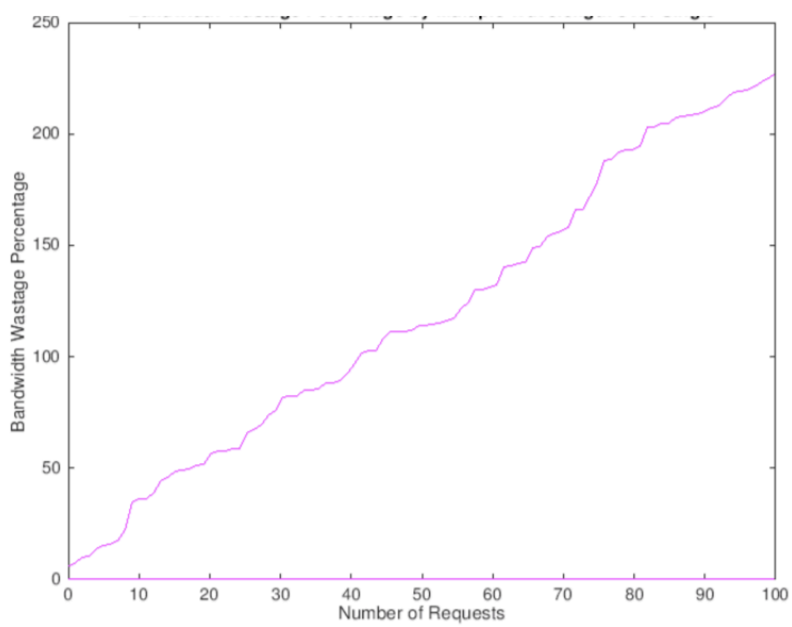

Figure 4.4: Percentage of bandwidth wastage by EBH over NBH

4.2.2 Average Delay

Figure 4.5 evaluates the average delay of request. EBH has less delay compared to NBH. Multiple wavelength allocation supports the parallel transmission. Any request is split into four equal parts and then they are send over four wavelengths which lead them to have one-fourth times average delay of NBH. This would be one-eight in a eight wavelengths system.

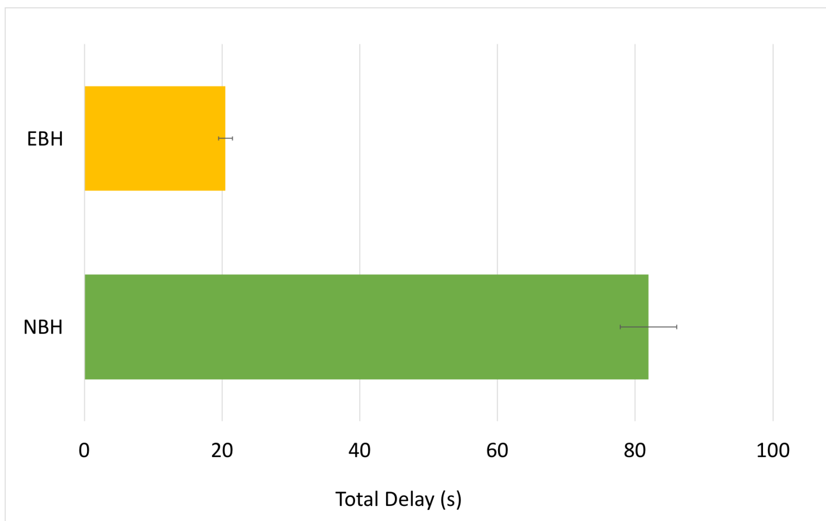

Figure 4.5: Average Delay: NBH & EBH

4.3 Priority Class Effect in Delay and Bandwidth Wastage

We add priority class in the methods P-NBH, P-EBH, and P-DBH. We compare the system's total delay and also the total delay to transmit A1 class priority requests. In Fig. 4.6, the solid bars depict the total delay of the system and patterned bars indicate the A1 class data transmission. Here, the total delay is calculated by as follows: Transmission end time - Request arrival time.

The grant requests have different arrival times. The NBH and EBH methods do not care about the priority classes. They process the grant based on the arrival time. For example, if an A1 class grant request arrives after 99 B3 or A3 class requests, these two methods would allow transmitting this A1 class grant after transmitting those 99 requests. Fig. 4.6 shows that there is not much difference

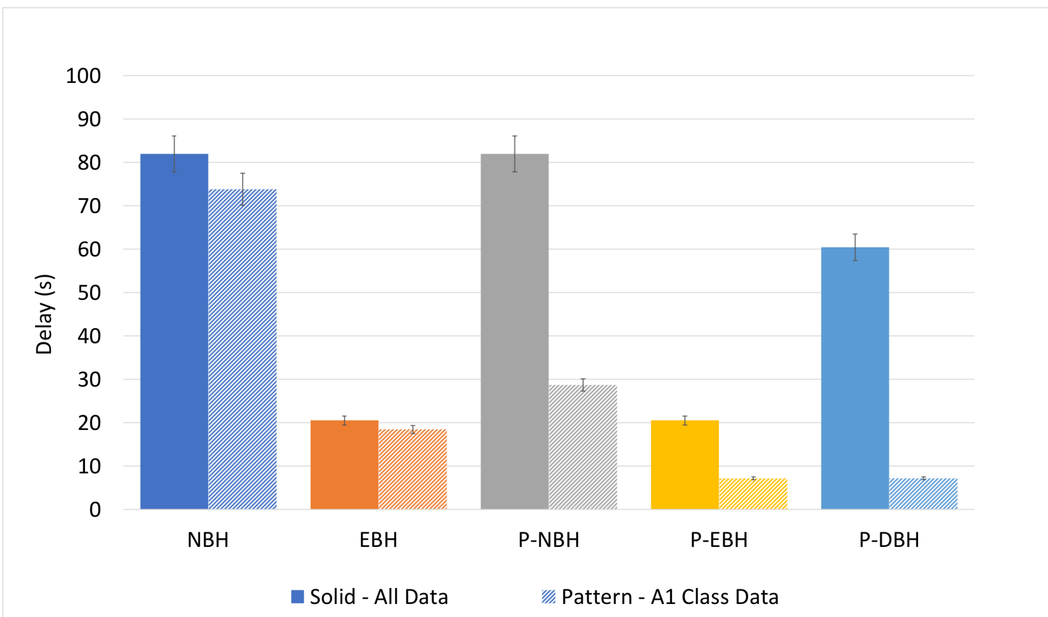

Figure 4.6: Total Delay

in the total delay of the system and the total A1 data transmission delay in NBH and EBH. Contrarily, the rest of the three proposed methods show significant improvement in terms of the A1 class transmission delay as they allow transmission higher priority data before the lower ones. Among these five methods, P-EBH and P-DBH show almost same and the best performance. In terms of total delay of the system, EBH and P-EBH show the best output as these two methods support parallel transmission.

Figure 4.7 evaluates the wasted amounts of the bandwidth from the guard bands. According to the above mentioned example, if an A1 class grant request arrives after 99 B3 or A3 class requests, these two methods would allow transmitting this A1 class grant after transmitting those 99 requests.

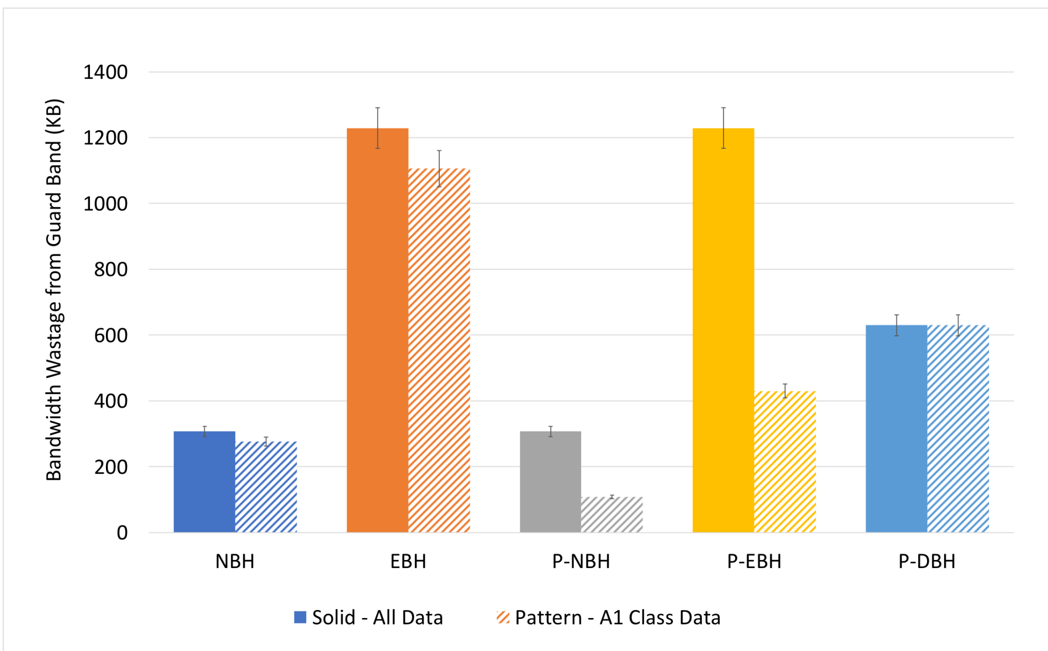

Figure 4.7: Total Bandwidth Wastage for A1 Class Data Transmission

Figure 4.7 shows the total bandwidth wastage amount for all requests and for A1 class data transmission. The EBH method has the highest amount of wastage. This is due to the use of four times more guard bands than NBH/P-NBH for parallel transmission. Among these five schemes, P-NBH has the minimum wastage for all and also for A1 class transmission.

4.4 Small-sized Grant Transmission

We already have seen that EBH or P-EBH would add 4-times more guard-band than NBH or P-NBH. Although the parallel transmission reduces the average delay in this scheme, the bandwidth wastage increases with the number of requests. If a grant size is small, then there is a chance that multiple wavelength allocation may increase the amount of bandwidth wastage to send the data split.

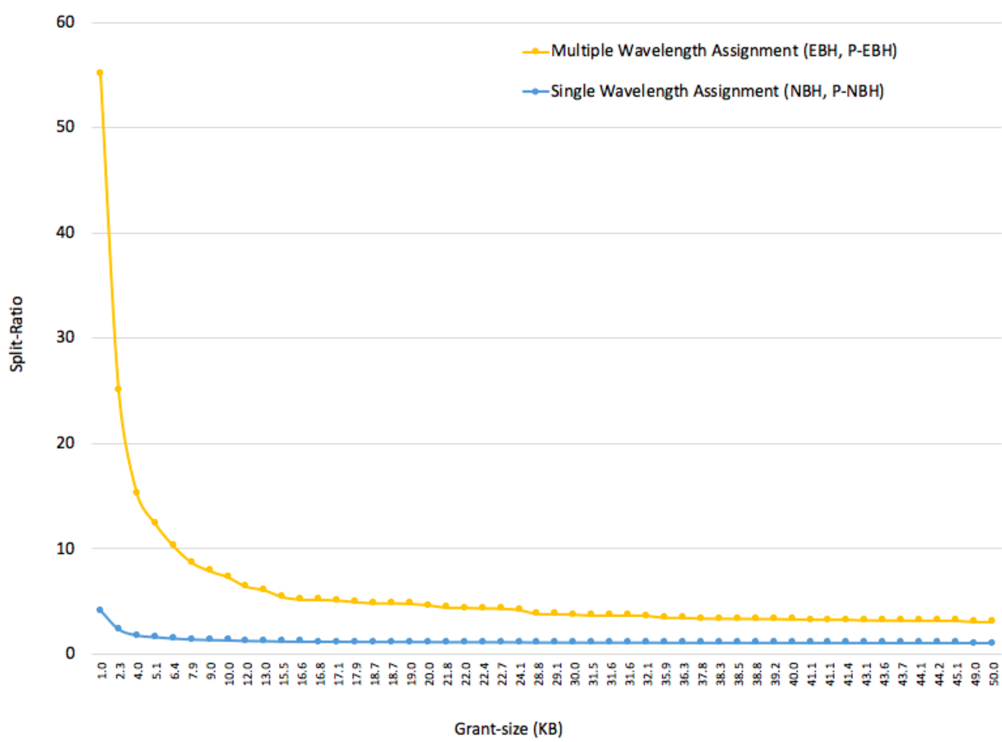

Figure 4.8: The relationship between grant size and split-ratio

It is necessary to know the minimum size of the grant that should not be split whether it is a high or low priority data. Therefore, we define a parameter, named Split-Ratio (γ), which is the ratio of total transmitted data (grant + guardband) and the total grant.

$$Split\ Ratio\ (\gamma) = \frac{Grant + Total\ Guardband}{Grant}$$

For this measurement, we generated 100 requests of small-sized data where $0 < range \leq 50$ KB and guard-band is 3 KB. Figure 4.8 shows the γ relationship with the grant-size. We observe that the ratios converge after 15 KB which is three times the guard-band. Thus, we set the d_{low} (minimum a grant-size that is allowed for multiple wavelength assignment) at 15 KB. This is the threshold value for a grant-size to decide whether it would be transmitted by single or multiple wavelength(s).

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this thesis, we propose five Dynamic Wavelength and Bandwidth Allocation schemes and compare their performances. Multiple wavelengths decrease the total delay, but it is not advantageous to transmit a small request through many paths. We find that the optimum size of data is four times the guard band in a four wavelength NG-PON2 system. The main disadvantage here is the bandwidth wastage. On the other hand, single wavelength increases the total delay, but it is more bandwidth efficient. From the previous chapter, we know that both NBH and EBH schemes do not guarantee the faster transmission of any high priority data. The schemes with priority class inclusion show significant improvement in the total delay of the high priority data as those are sent first. P-EBH shows better result as it also provides parallel transmission to the system. Although, P-NBH has higher delay than P-EBH, it results in minimum bandwidth wastage. Finally, P-DBH, the hybrid of P-NBH and P-

EBH, supports parallel transmission to the A1, B1, A2, B2 class requests and single wavelength allocation for the rest. This ensures minimum delay for the high priority data and minimum bandwidth wastage for the lower ones.

5.2 Future Work

All the schemes either use single or all wavelengths. The proposed algorithm does not take into consideration that there can be an optimal number of wavelengths to allocate.

The effect of the energy usage can be studied. We could utilize the traffic information from several previous time slots and assign different weights to them to exploit the historical traffic information to save energy.

Since security is an important characteristic in any communication system, this work can be expanded by incorporating integrity, privacy, and other related features.

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