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Bandwidth Utilization and Management Algorithms (BUMAs) for NG-EPON

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Abstract

An upcoming capable technology named as Next generation Ethernet passive optical network (NG-EPON); to handle enormous bandwidth and effective distribution requirements for prospective Internet based services. Standardization procedures for NG-EPON are in progress. Transmission of data traffic from Optical Network Units (ONUs) towards Optical Line Terminal (OLT) in NG-EPON is carried out through four wavelengths each operating at a data rate of 25Gbps. Dynamic wavelength and bandwidth allocation (DWBA) algorithms are needed for the efficient arbitration of the bandwidth resources between the subscribers. In this paper, we have proposed two different DWBA algorithms for NG-EPON; DWBA-I and DWBA-II. DWBA-I is a Quality-of-Service based algorithm that has been designed to manage the different types of data traffic in NG-EPON. DWBA-I performs better than the different existing DBA algorithms in terms of packet delay, completion time and packet drop ratio. DWBA-II is an algorithm designed to meet the system requirement specifications of NG-EPON and handle traffic requirements of subscribers in a cost effective manner. DWBA-II algorithm is comparatively analyzed and evaluated with First-Fit-DWBA and Modified-IPACT algorithms. Performance of DWBA-II is better on the basis of average delay, grant utilization, completion time and packets drop ratio. Performance of DWBA-I and DWBA-II has been evaluated through simulation results.

Keywords Dynamic wavelength and bandwidth allocation (DWBA) · Wavelength Agile · Next Generation-EPON · Quality-of-service · Multi-scheduling-domain · Average-packet-delay (APD) · Average-completion-time (ACT) · Packet-drop-ratio (PDR) · Grant-utilization (GU)

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1 Introduction

Requirement of overwhelming and fast data services is consistently rising every day. With the modern technologies like Internet of Things (IoT), where simple objects have network connectivity and for sure their functionality needs network connectivity for the sending and receiving of data. Some of IoT applications like smart homes, smart objects, smart grids and smart cities will dominate the world [1]. Trends are showing that transmission of data in an access network is rising-up rapidly and will reach thousands of Exa-byte in future [2]. Demand of more bandwidth crafts the path for commercial implementation of Passive Optical Networks (PON). High Data transmission capacity and cost effectiveness are main benefits of PON [3]. Ethernet PON (EPON) is a capable solution for access networks which can handle high bandwidth requirement of end users. EPON combines low-cost Ethernet equipments and low-cost passive optical components; thus has a number of advantages over traditional access networks, such as larger bandwidth capacity, longer operating distance, lower equipment and maintenance cost, and easier updating to higher bit rates [4]. EPON is a simple technology to setup, as there are no necessary conversions for connecting Ethernet networks. EPON can be categorized as: Time-Division-Multiplex (TDM-EPON), Wavelength-Division-Multiplex (WDM-EPON) and hybrid (TWDM-EPON). A single wavelength channel is used by TDM-EPON for upstream/downstream directions and provides a cost effective network solution. Dedicated wavelength channels are provided by WDM-EPON for upstream/downstream directions to all ONUs [5]. Hybrid (TWDM-EPON) combine the properties of both TDM-EPON and WDM-EPON to form a more flexible EPON architecture [6, 7]. In TWDM-EPON, we deploy an Arrayed-Waveguide-Gratings (AWG) at central office(OLT). AWG allocate wavelength to a coupler (splitter), which then transfers time slots by using TDM. Traffic transmitted from different ONUs is forwarded through coupler (combiner) and AWG in upstream directions [8].

Demand of bandwidth hungry applications in corporate/business and residential customers is rising every day. 1G EPON could not manage to cater bandwidth requirements of all subscriber and operators due to capacity constraints. Evolution in EPON technology should be done to accommodate heavy bandwidth demands. Corporate and residential users in access are increasing very rapidly. Very high data rates are needed by the subscribers because of the bandwidth intensive applications like 3D gaming, HD video services, parallel video streams, concurrent online sessions etc. In future access networks we need to have huge bandwidth, very large number of subscribers, larger coverage area for access and cost effective solution. Next Generation-EPON would be the future access network that can provide Exa-bytes of data, coverage area of up to 100km, data rate of 10Gbps and/or 25Gbps on a single wavelength and lower cost. NG-EPON would be the backbone for all the necessary and critical future services like smart homes, smart cities, smart objects, smart grids and many more. Integration of EPON with wireless access networks would also be a cost effective and comprehensive solution to provide high capacity to the subscribers to meet the future needs [9]. Group formed by IEEE is doing efforts for exploration of NG-EPON, that can handle rapid increase in bandwidth requirement of future access technology users.

To cope with bandwidth demands of end users, a new standard known as Next-Generation EPON (NG-EPON) has been developed by International Telecommunication Unit (ITU). NG-EPON is future access technology which can provide 100Gb/s in downstream, 25Gb/s on a single wavelength in upstream direction and range of coverage area from 20km to 100km. NG-EPON can provide authoritative abilities to Internet Service Providers (ISP) for meeting unprecedented bandwidth requirements. NG-EPON would broader coverage area and increase data transmission speed [10]. NG-EPON would provide highly reliable communication as compare to existing old EPON. Convergence of multiple services network into one Optical-Distribution-Network (ODN) could be done through NG-EPON. NG-EPON would enable the introduction of new and efficient architectures that could be adjusted in depth to meet changing and evolving demands of the subscribers. NG EPON facilitates communication rate of 100Gb/s in downstream and 25Gb/s per channel in upstream directions. NG-EPON enables new business opportunities for ISPs, because of its capability to deliver 25Gbps to a single subscriber [11]. Main achievable goals through NG-EPON are very large number of end users covering larger service area, very high bandwidth including high per PON/per trunk data rates and low cost for FTTH/FTTB/ FTTC deployment implementation. The existing EPON could be upgraded to NG-EPON by substituting OLT and ONUs as depicted in Fig. 1.

Multiplexing technique selected for NG-EPON is TWDM [12]. By full service area network (FSAN), this decision has been made upon several factors

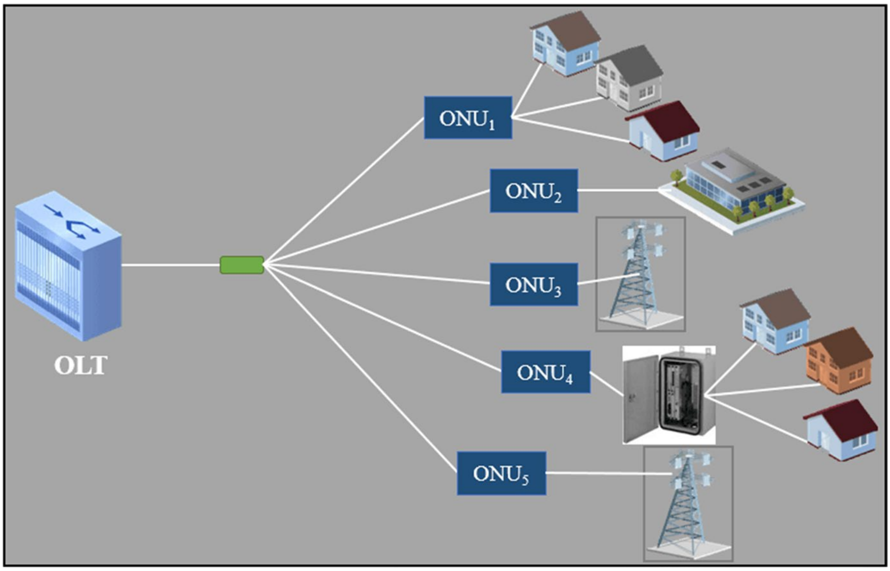

Fig. 1 Next generation EPON

like modern technology, system performance, power and cost efficiency. NG-EPON supports four wavelength channels (1 to 4), subscribers can utilize channels in a "pay-as-you-grow" model on each fiber. Key enabling technologies and devices up-gradation, assurance of security due to broadcasting nature of traffic in downstream, eavesdropping and efficient/optimized bandwidth management of upstream traffic are the different problems for NG-EPON that should be addressed [13]. A phenomenon of DWBA would be implemented at OLT for dynamically distribution of bandwidth between subscriber ONUs [14]. DWBA helps to arbitrate traffic to avoid conflicts between end users (ONUs).

Bandwidth management problem on multiple wavelength channels in EPON could be addressed by three different proposed design classifications; Multi-Scheduling-Domain (MSD), Single-Scheduling-Domain(SSD) and Wavelength-Agile (WA) [15]. In MSD-EPON, one single wavelength channel is granted to an ONU. In SSD-EPON, all available wavelength channels are assigned to one ONU at single instance of time. WA-EPON provides more flexibility of wavelength channel allocation and sharing, as variable number of wavelengths could be assigned to any ONU at different demanding hours. Detailed discussion on bandwidth management based design classifications would be done in Sect. 2.

The objective of this paper is to design, develop and implement novel DWBA algorithms for (MSD and WA) design architectures of Next Generation-EPON, to provide bandwidth management and utilization in an efficient manner. The main contribution of this paper is the following:

- We proposed the architectures for the NG-EPON that provides support for handling the different traffic requirements of the subscribers.
- Our proposed architectures for Next Generation EPON also provide Quality of service support to the users.
- We designed and implemented two different DWBA algorithms for NG-EPON flavours; DWBA-I for MSD-EPON and DWBA-II for WA-EPON.
- Our proposed DWBA algorithms are designed on the basis of future requirements of subscribers.
- The performance of our proposed bandwidth utilization and management algorithms are evaluated with the existing solutions on the basis of packet-delay, completion-time, packet-drop-ratio and grant-utilization.

The rest of the paper is organized as follows: Sect. 2 introduces different design classifications of NG-EPON: SSD-EPON, MSD-EPON and WA-EPON. Sect. 3 discusses different existing algorithms that can address DWBA problem in NG-EPON through suitable re-adjustments. In Sect. 4, some new DWBA algorithms are proposed that can provide better utilization of the bandwidth resources. In Sect. 5, performance evaluation and analysis of proposed DWBAs is done comparatively with already developed DWBAs. Section VI concludes our paper.

2 Bandwidth Allocation Based Design Architectures for NG-EPON

Downstream wavelength channels in EPON are accessed by OLT for data transmission. To transmit data OLT does not require any arbitration mechanism. For upstream transmission, OLT grants channel access to different ONUs. OLT allow ONUs to transmit their respective data in upstream direction. Based on OLT arbitration for channel access, NG-EPON could be classified as following design classification.

2.1 Multi-Scheduling-Domain (MSD)-EPON

OLT grants a wavelength to one ONU at single instance in MSD-EPON. Each wavelength channel is operating as an individual scheduling domain because one ONU would be assigned a single wavelength at single instance of time. Multiple ONUs could transfer data in parallel on different wavelengths. DWBA implemented at central office equipment would be responsible for allocation of transmission window to a specific ONU. MSD-EPON works similar as like TWDM-EPON. Existing DWBA algorithms for TWDM-EPON can be used by MSD-EPON with appropriate adjustment of necessary parameters [16].

2.2 Single-Scheduling-Domain (SSD)-EPON

OLT provides access of all wavelengths to an ONU at a single instance in SSD-EPON. All four wavelength channels are operating as one scheduling domain because only one ONU would be assigned all four wavelengths at single instance of time. DWBA implemented at central office equipment would be responsible for allocation of transmission window to a specific ONU. SSD-EPON appears to be a replica of TDM-EPON. Existing bandwidth management DWBAs for TDM-EPON can be used by SSD-EPON with necessary parameter based adjustments.

2.3 Wavelength-Agile (WA)-EPON

WA-EPON is a combination of SSD and MSD. In WA-EPON, OLT can grant single wavelength or multiple wavelengths in parallel to different ONUs. If an ONU wants to transmit on multiple wavelengths, it should have tunable lasers. One or more than one wavelength channels can be operating as a scheduling domain, because an ONU could be assigned a single wavelength or more than one wavelengths at single unit of time. To effectively schedule transmission, an arbitrator is needed to prevent collision in upstream direction. WA-EPON is a flexible design architecture to meet varying needs of subscribers.

Table 1 Comparison of NG-EPON Design Architectures

Parameters	MSD	SSD	WA
Working principle	An ONU transmits on different channels. I–I	An ONU transmits on all channels. I–All	An ONU transmit on one or multiple channels. I–I/I–Many
Multiplexing Type	Same as TWDM	Same as TDM	Same as TWDM but more flexible
Current-State	Already developed DWBA of Hybrid(TWDM)-EPON can be utilized by MSD-EPON through suitable parameters adjustment	Already developed DBA of TDM-EPON can be utilized by SSD-EPON through suitable parameters adjustment	Existing or already developed DWBA schemes could not be used for WA-EPON
Algorithms	Earliest Finish Time (EFT)	Interleaved Polling with Adaptive Cycle Time (IPACT)	First-Fit

Three different DWBA based (design) architectures for NG-EPON are comparatively analyzed in Table 1. In the next section we will discuss some existing DBA algorithms.

3 Different Existing DBA Algorithms

DBA is decision based phenomenon used for bandwidth management and allocation. DBA is implemented at OLT and is utilized for the effective distribution of bandwidth. Major role of DBA is to minimize idle slots of upstream channels [17]. Existing DBAs for TDM-EPON can be used for SSD by making necessary parametric configuration according to requirements and limitations of future access network. IPACT [18] is a TDM based DBA algorithm that can by used by SSD-EPON. IPACT polls request and grants time-slice based transmission in Round-Robin (RR) fashion. IPACT allows ONUs with high traffic loads to easily monopolize channel for a large period of time and thus cause ONUs with low traffic loads to suffer.

Principle of MSD-EPON is similar to TWDM-EPON. DBA algorithms developed for TWDM-EPON could be utilized by MSD-EPON by making necessary parametric adjustment according to standardized factors of NG-EPON. Following DBA algorithms [19] for TWDM-EPON could be utilized for MSD-EPON. Static-Wavelength-Dynamic-Time (SWDT) [20] DBA scheme assigns wavelength slots statically and Dynamic-Wavelength-Dynamic-Time (DWDT) [21] DBA scheme assigns wavelength and time slots dynamically to ONUs. DWDT manages log of all wavelength channels for dynamic assignment to ONUs as per their requests. Different DBA algorithms with QoS support have been designed for Hybrid-EPON. DBA-I, DBA-II and DBA-III are three algorithms. DBA-I is the algorithm for intra-ONU scheduling with fairness support. DBA-II provides both inter and intra ONU scheduling. In DBA-III, two channels are used in parallel, first one for high data rate and second for low data rate [22]. Earliest-Finish-Time (EFT) [23] and EFT-Void Filling (EFT-VF) [24] are two online algorithms for upstream channels scheduling. EFT helps to schedule requests of ONUs on the wavelength channels that becomes free earliest. Scheduling is performed in an imminent manner to assign transmission window to ONU when their Reports arrive at the OLT. Transmission of data traffic on the earliest available wavelength ensures an early completion time. EFT allocates earliest wavelength to ONUs whose previous transmission finishes early as compared to other wavelength channels. EFT-VF is modified version of EFT. EFT-VF reduces the average waiting time as compared to EFT. Transmitting data on single channel has void spaces/intervals between to consecutive transmission. EFT-VF works to utilize these voids to enhance the resource utilization. Voids available for allocation should be of a reasonable minimum possible size that can be utilized to improve network performance. A DBA based on Class-of-service [25], classifies traffic into two priority based sub-groups. Channel allocation can be done into two segments: segment one for higher priority data traffic and segment two for low priority data traffic.

Water Filling (WF) DWBA algorithm has been proposed for WA-EPON [26]. In WF-DWBA, bandwidth is assigned to a single ONU in a way to fulfill its requirement amicably. Utilization of wavelengths is converged in equivalence. Channels are arranged in terms of utilization in WF algorithm. At first step, a grant is assigned on the channel which is minimal utilized, so that it could be matched with second minimal used wavelength. In case, variance between two consecutive wavelengths is greater than next required bandwidth, the allocation would be done at the first wavelength. In WF-DWBA, an ONU is allocated bandwidth grants on several wavelengths subject to required bandwidth and difference between finish time of wavelengths in last instance of distribution. WF-DWBA behaves in a same manner as like modified version of IPACT [18] (also named as Modified-IPACT). Modified IPACT is an implementation of legacy IPACT by considering all four wavelength channels as a single channel. Recently, First-Fit-DWBA [27] has been designed for WA-EPON that provides improved performance as compared to WF-DWBA. First-Fit allocates a grant on a single wavelength channel; a channel whose availability is earliest as compared to all other channels. Main idea of First-Fit algorithm is to manage availability of channels all the time. According to First-Fit-DWBA, allocation of bandwidth grants on single channel is better in terms of efficiency as compared to concept of leveling channel resources on all available channels for each allocation. ONUs are given bandwidth grant in parallel by using First-Fit.

Already developed algorithms for TWDM-EPON can be utilized for MSD. But, still we require to design and implement neoteric DWBA schemes according to the demand and needs of future access networks. EFT and EFT-VF are the two existing schemes that could be used for MSD-EPON. Both EFT/EFT-VF are schemes based on online scheduling framework and are wavelength assignment algorithms that do not cater ONUs request while performing dynamic bandwidth allocation. Similarly FF-DWBA is an algorithm designed for WA-EPON. FF-DWBA is based on online scheduling framework and is a wavelength assignment algorithm that also do not consider ONUs requests while allocating wavelength channels to different ONUs. As we know that for future access networks (NG-EPON), requirement of customer ONUs is a very important factor for service providers. Secondly in online scheduling framework, bandwidth allocation is performed without having the sufficient knowledge of all customer ONUs. So, there is a need to design DWBA algorithms that can perform bandwidth allocation in a more effective and improved manner than the existing algorithms based on future needs and requirements of subscribers. Two DWBA algorithms have been proposed for NG future access network in next section; first DWBA algorithm is for MSD-EPON and the second is for WA-EPON. The new algorithms are designed by keeping in view the needs of future access networks (NG-EPON).

4 Neoteric DWBA Algorithms for NG-EPON

We have 4 wavelength channels in our proposed NG-EPON architecture for upstream traffic transmission. ONUs share the wavelength channels in TDM fashion. Upstream channels in our architecture are arbitrated by the MPCP protocol. Request and grant allocation process on the basis of subscribers demand is handled by the Report/Gate messages. As we know, a DWBA is needed to arbitrate the upstream wavelength channels to different ONUs. DWBA is also responsible for management and allocation of wavelengths and timeslots to subscribers according to their demands. We have proposed two different DWBA algorithms for NG-EPON; one for MSD-EPON and other for WA-EPON. The detail of both the algorithms are discussed below.

4.1 DWBA-I

As we know that NG-EPON would be the backbone for all modern services like smart homes, smart cities, smart grids and many more. A very important functionality known as Quality of Service (QoS) have to be essential part of future access network services. Diversified customers would be requiring different types and levels of services from their service providers. In NG-EPON, number of channels for upstream transmission would be quite lesser than the number of ONUs. So, our arbitration mechanism implemented at OLT should be quality of service based. Currently no such bandwidth allocation algorithms with QoS support specifically for NG-EPON exists. System Requirements for implementation NG-EPON are regarding the Coverage / Reach of subscribers and is specified as a range from 20Km to 100Km. Our proposed DWBA-I is designed to meet systems requirement of NG-EPON along with QoS support according to future demands of subscribers. We have proposed an algorithm named as DWBA-I for MSD-EPON design architecture of NG-EPON. The architecture of MSD-EPON for which we have proposed our algorithm is shown in Fig. 2. Quality of Service (QoS) support has been provided in our DWBA-I algorithm to manage access network traffic in categoric and suitable manner.

Data traffic for access network has been divided into two categories: Lower Priority Traffic (LPT) and Higher Priority Traffic (HPT). We will use two transceivers;

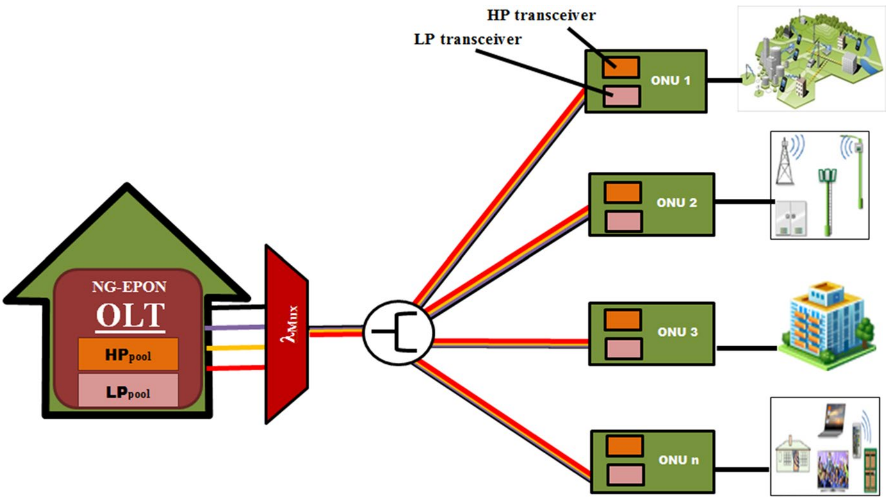

Fig. 2 NG-EPON architecture for DWBA-I

one for LPT and other for HPT. HPT traffic would be delay sensitive traffic with Constant-Bit-Rate (CBR) and heavy bandwidth demanding applications with Variable-Bit-Rate (VBR). Corporate premium traffic for businesses and critical traffic for Electronic Commerce business activities would also be part of HPT. Bulk traffic, audio/video streamed traffic, non-business lesser delay sensitivity having VBR is clubbed together as LPT. HPT and LPT would have dedicated wavelengths for the transmission of specific types traffic. Higher priority traffic would be handled by HPT dedicated transceivers and lower priority traffic would be managed by LPT dedicated transceivers. OLT side would have separate pool-sections for LPT and HPT. Reports for HPT would gathered in HPT pool and reports for LPT would be gathered in LPT pool. DWBA-I is proposed to handle the bandwidth requests of future subscribers in a better and more effective manner. NG-EPON is heterogeneous in nature, our DWBA-I is designed to handle this varying distance property. ONUs in NG-EPON would be situated at distances ranging from 20 to 100 km in NG-EPON. Our proposed NG-EPON architecture provides a single wavelength for LPT and three wavelengths for HPT. Our DWBA-I algorithm based on QoS is shown below.

QoS based DWBA-I Algorithm for NG-EPON

```
Process Starts // QoS based DWBA-I
RPTs received at the OLT and maintained in two pools (HPT & LPT)
List () { //Apply List function on both pools HPT & LPT
Arrange ONUs RTT wise in increasing order;
If( Two ONUs RTT are equal) then
ONU with SPT comes first in the List;
Complete arrangement of ONUs and sorting process ;
List_HPT; // Arranged list for HP traffic
List _LPT; // Arranged list for LP traffic
} // End of List ()
While (Jobs left in the pool){
List (); // List function called to form lists for HPT & LPT pool
Spawn If(wavelength available for HPT)then
Allocate slots to the ONUs according to List_HPT;
Else{
Wait for the wavelength to become free;
Allocate slot to the ONU according to List_HPT; } // End of else
Spawn If(wavelength available for LPT)then
Allocate slots to the ONUs according to List_LPT;
Else{
Wait for the wavelength to become free;
Allocate slot to the ONU according to List_LPT; } // End of else
Transmit the data on allocated wavelength followed by RPT
} // While Ends
Process Ends
```

Our DWBA-I is a centralized bandwidth distribution algorithm. It manages the LPT and HPT traffic in two different separated pools; HPT and LPT. Reports (RPTs) from all ONUs are received at the OLT, segregated into HPT and LPT category and are then sent to their respective pools. In each pool, ONU requests are arranged into increasing order according to the ONUs distance from OLT (referred as Round-Trip-Time (RTT)). If more than one ONU requests having same RTT are in pool, we would place ONU having shortest transmission request higher in order as compared to other ONUs. We would be applying SPT in case of having RPTs of ONUs with same RTTs. DWBA-I works as a combination of offline-online algorithm for HPT. We wait till the time when a wavelength becomes free; then all requests in the pool are arranged using above mentioned principle and these requests are allocated on the free wavelength. Allocation to ONUs is intimated through gate messages. Lower priority requests are gathered in the LPT pool and as there is one wavelength assigned for LPT, we have to gather all the RPTs of all the ONUs in LPT pool, then apply above mentioned algorithm principle (RTT + SPT) arrangement and allocation of channel to ONUs. For LPT, we implement the DWBA-I in a pure offline fashion.

The operational flow diagram of EFT for 3 ONUs allocation on 3 wavelengths is shown in Fig. 3. The operational flow diagram of DWBA-I for 3 ONUs allocation on 3 wavelengths (2 for HPT and 1 for LPT) is shown in Fig. 4. In EFT, when a wavelength is assigned to an ONU for the transmission of its data, that wavelength could not be assigned to any other ONU during that time to any other ONU what ever the delay factors exists in completion of transmission of that specific ONU. Our DWBA-I is an algorithm based on offline-online bandwidth assignment. DWBA-I performs bandwidth allocation based on ONUs request and also handles ONUs traffic based

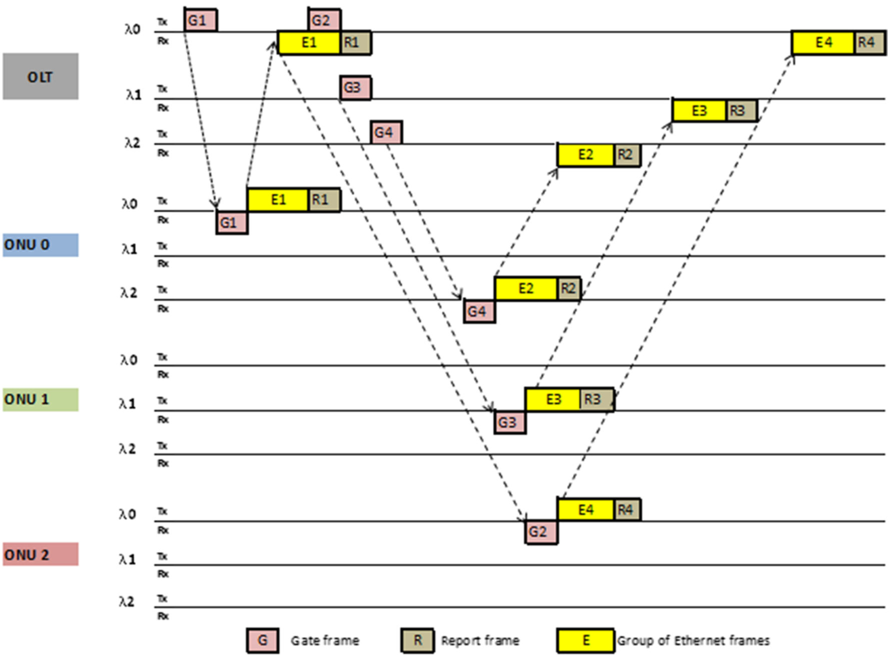

Fig. 3 Execution flow of EFT

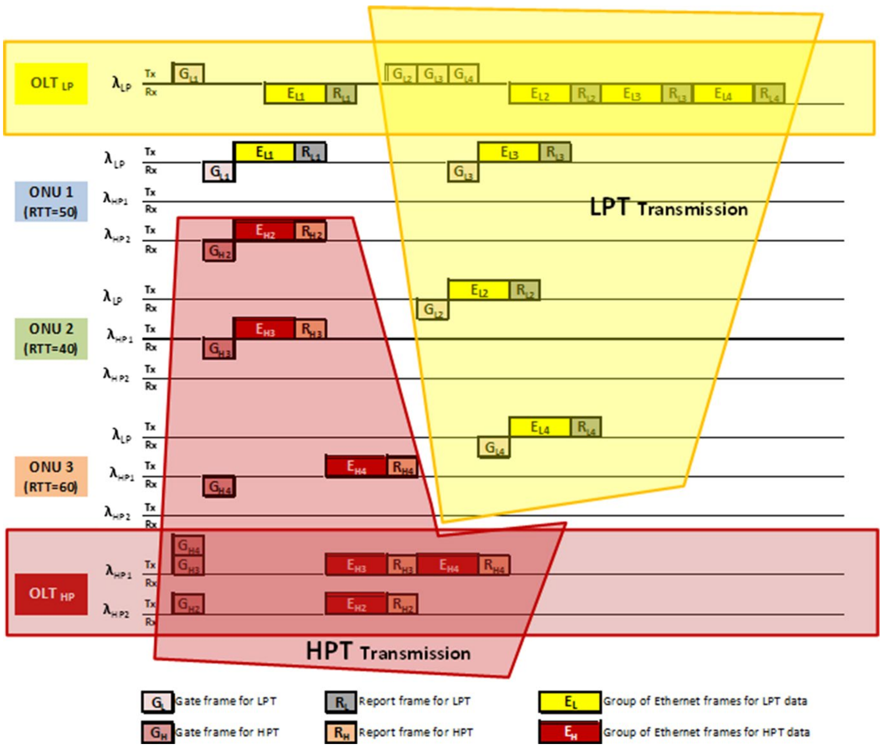

Fig. 4 Execution flow of DWBA-I

on Quality of service in two parallel pools maintained at OLT. It can be clearly seen from Fig. 4, that HPT and LPT traffic requests are handled in parallel by our DWBA-I. In Fig. 3, four requests for transmitting four groups of Ethernet frames (E) are executed through Gate(G) and Report(R) messages by using three wavelengths. In Fig. 4, again four requests of same ONUs (segregated into 4 LPT & 3 HPT) for transmission are shown. As we know that for our DWBA-I, each ONU send groups of Ethernet frames and reports for HP and LP traffic by using separate wavelength channels. In Fig. 4, first transmission is only for LP traffic and is represented by E_{L1}. All the three remaining transmissions are for both HP & LP traffic. LP Ethernet data frames are represented as E_{L2}, E_{L3}, E_{L4} and HP Ethernet data frames are represented as E_{H2}, E_{H3}, E_{H4}. LP data transmission is outlined with yellow shaped box and HP data transmission is outlined with red shaped box in Fig. 4. It can be clearly seen from Figs. 3 and 4 that our proposed DWBA-I performs more efficiently than EFT.

4.2 DWBA-II

There are different new trends observed in access networks user traffic behavior. Residential and business subscribers have flexible requirements on different demanding hours, it shows that ONUs have different bandwidth requirements at different timings in a day. Secondly, distribution of traffic is varied; real scenarios suggest that only few percentile of subscribers use 50% of their allocated bandwidth. In NG-EPON, subscriber would be provided service on the principle of “pay as you go” to make a cost effective solution. It would be providing quality oriented service at service oriented cost. While considering the operational requirements of NG-EPON, we have to cater deployment and operational cost of NG-EPON setup. The subscribers have to bear all the relevant costs regarding the services. Diversified customers would be requiring differentiated services from service providers. NG-EPON with complex situations will exist, where heavy flows and mice flows can coexist in one network. We have proposed DWBA-II by keeping in view the two different types of subscribers based on their required traffic flows in future network. We have segregated our ONUs into two types; Heavy Loaded ONUs (HLO) and Light Loaded ONUs (LLO). We have proposed an algorithm named as DWBA-II for Wavelength Agile-EPON design architecture of NG-EPON. The NG-EPON architecture for which we have proposed our algorithm is shown in Fig. 5.

For the purpose of the DWBA implementation, we have categorized data handling into two segments. One is the ONU side data traffic management and other is OLT side handling of data traffic in our NG-EPON network architecture. At ONU side, a single queue capable of receiving all the types of data traffic is used. The data traffic coming from the multiple users can be of any type either; delay sensitive traffic, traffic with no-delay sensitiveness with CBR, audio/video streamed non-business data with VBR and bulk traffic with huge amount of bandwidth requirement. A Report message would be transmitted by each ONU towards OLT based on size of data to be transmitted by the ONUs. At OLT side, we have a pool of Report messages from all the ONUs. For our DWBA-II, the OLT would be capable of classifying ONUs Reports in HL pool and LL pool. The requests of HLO will be placed in HL pool and requests of LLO will be placed in LL pool. ONUs that can use more

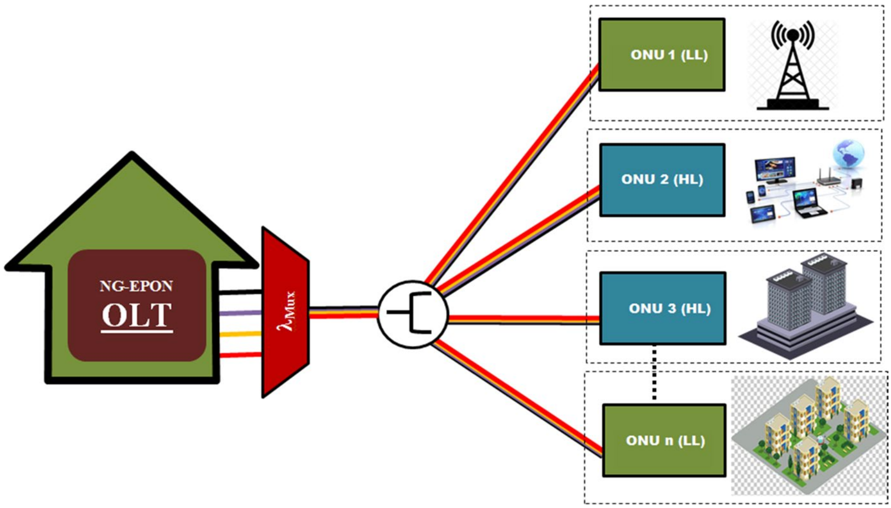

Fig. 5 NG-EPON architecture for DWBA-II

than 50% of bandwidth has been categorized as HLO and ONUs which can use less than 20% of allotted bandwidth has been categorized as LLO. The subscribers would be paying more for heavy bandwidth requirement belongs to the HLO group and the subscribers paying lesser belong to the LLO group. Four wavelength channels are available in our NG-EPON architecture. Three wavelengths are allocated to the HL pool and one wavelength is allocated to LL pool. Our DWBA-II is comprised of two modes. Mode 1 is for the HLO traffic and Mode 2 for LLO traffic.

All Report messages for HLO are gathered in HL pool. Mode-1 will be used for bandwidth allocation of HLO. We arrange HLO in increasing order based on their processing time (PT). ONU with minimum PT would come at top and ONU with maximum PT would come at last of list. We use a function List_HLO to make the arrangement of ONUs for allocation. Then the availability of wavelength channels would be checked. If wavelength is available, top two ONUs would be assigned the requested slots on single wavelength. After scheduling transmission of ONUs again check wavelength availability. If wavelength is available, then pick up two ONUs from the List_HLO whose PT is less than other and schedules them on the available wavelength. If no free wavelength is available, then wait till the wavelength becomes free. Schedule transmission of ONUs on the available wavelength, when it becomes free. Repeat this allocation until all requests in the List_HLO are served. Again List_HLO function would executed on the Report messages received in the pool (P_HLO). After the formation of List_HLO and the availability of wavelength, allocation of wavelength channel would be performed as mentioned above. HLO allocation is performed in an online manner. In mode-1, two ONUs are allocated on a single channel at one instance of time. An ONU would be assigned a single wavelength channel at one time; this will also help to minimize frame re-arrangement problem at OLT in NG-EPON. Once an ONU completes its communication on assigned wavelength, then this wavelength would be allocated to the next subscribers ONU. Pseudo-code of mode-1 for our proposed DWBA-II is given below.

DWBA-II Algorithm Mode-1 for Heavy Loaded ONUs

```
Process Starts // DWBA-II mode-1 (HLO)
Receive RPTs from HLO in pool (P_HLO)
List_HLO() {
List_HLO = Arrange ONUs in the ascending order of PT; }
While (P_HLO!=Null)
{
If(wavelength free)
List_HLO();
Else
{ Wait for the availability of wavelength;
List_HLO();}
Allocation:
Allocate free wavelength to 2 ONUs at the top in List_HLO;
If (ONUs left in List_HLO)
{
If ( wavelength free)
goto Allocation;
Else
{ Wait for the availability of wavelength;
goto Allocation; }
} // End of current List_HLO
} // End of While loop
All the HLO completed transmission and no Reports left
Process ends
```

All the Report messages for LLO are gathered in LL pool. Mode-2 would be used for bandwidth allocation of LLO. All Reports from LLO are first gathered in pool (P_LLO). Then the List_LLO function would be executed on ONUs request to generate List for light loaded ONUs (List_LLO). We arrange LLO in increasing order based on their processing time (PT). ONU with minimum PT would come at top and ONU with maximum PT would come at last position of list. After the generation of List_LLO, wavelength availability is checked. When wavelength becomes available, timeslots are assigned to LLO according to the generated List_LLO. After the completion of first cycle for LLO, we would again check the status of Report messages in P_LLO. If the number of Report messages are less than half of the total number of LLO, we have to wait for more Report messages to be received in P_LLO. When Reports of half number of ONUs are received in P_LLO, we will execute the List_LLO function again to generate the sorted list for LLO. After the generation of List_LLO and the availability of wavelength channel, we would allocate time slots to ONUs in the List_LLO. Minimum half number of Report messages should in pool for the execution of DWBA-II algorithms mode-2 and allocation of time slots to LLO. Mode-2 continues to execute in the same manner till all LLO complete their job transmission towards the OLT. Mode-2 of our DWBA-II is executed in a half offline manner. The pseudo-code of Mode-2 for our proposed DWBA-II is given below.

DWBA-II Algorithm Mode-2 for Light Loaded ONUs

```
Process Starts //DWBA-II mode-2 (LLO)
Receive RPTs from LLO in pool (P_LLO)
List_LLO(){
List_LLO = Arrange ONUs in the ascending order of PT;
 }
If( wavelength available)
Allocate slots to ONU according to List_LLO;
Else
{ Wait for the availability of wavelength;
Allocate slots to ONUs according to the List_LLO ; }
Again receive Reports from LLO ;
while(P_LLO != null)
{ if( Half No. of Reports from LLO received at P_LLO)
{ List_LLO();
If( wavelength available)
Allocate slots to ONUs according to the List_LLO;
Else
{ Wait for the availability of wavelength;
Allocate slots to ONU according to the List_LLO; }
}
Else
Wait till Half number of LLO Reports received;
} // End of While loop
All ONUs completed their transmission and no RPTs left in pool;
Process ends
```

The operational flow diagram of First-Fit DWBA having 8 ONUs and 3 wavelength channels is shown in Fig. 6. The operational flow diagram of our proposed DWBA-II for 8 ONUs and 3 wavelength channels (2 for HLO traffic and 1 for LLO traffic) is shown in Fig. 7. Both FF-DWBA and DWBA-II are comparatively analyzed for same traffic requests from 8 ONUs. It can be seen from Fig. 6 for FF-DWBA, total completion time for 3 wavelengths is (33+33+35=**101**). Average completion time for FF-DWBA is computed to be **33.667**. On the other hand, it can be seen from Fig. 7 for DWBA-II, total completion time for same requests by 8 ONUs on 3 wavelength channels is (30+32+21=**83**). Average completion time for DWBA-II is computed to be **27.667**. The results showed that DWBA-II performs more effectively as compared to FF-DWBA. Comparative differences between our proposed DWBA-I and DWBA-II are given below :

- DWBA-I is for Multi-Scheduling-Domain design architecture of NG-EPON. Whereas, DWBA-II is for Wavelength-Agile design architecture of NG-EPON.
- DWBA-I is quality of service based algorithm in which the traffic of each ONU is segregated in two groups HPT and LPT. DWBA-I also caters the system requirement of NG-EPON regarding the Coverage and Reach of ONUs and is specified as a range from 20Km to 100Km. DWBA-II is an algorithm in which ONUs are categorized in two groups (HL and LL) based on their vol-

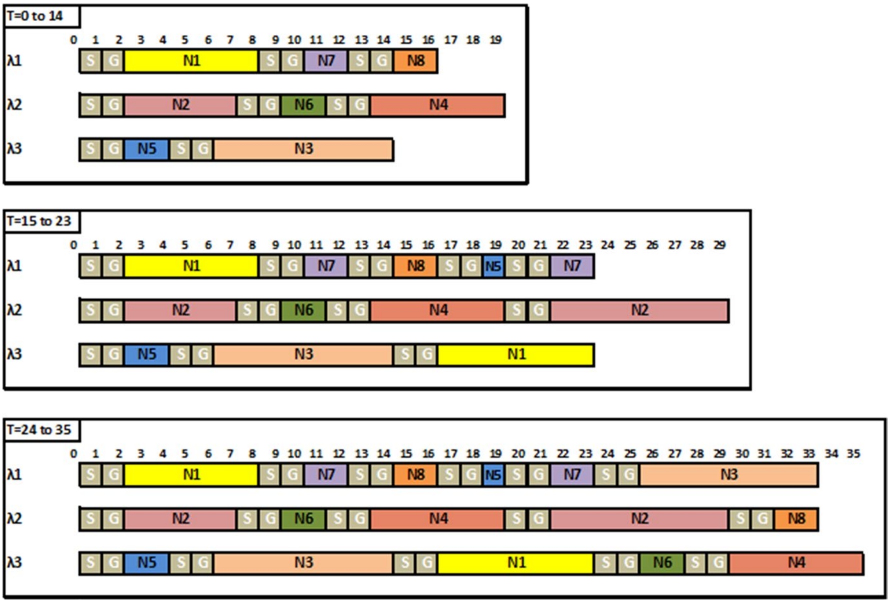

Fig. 6 Operational flow diagram of First-Fit DWBA

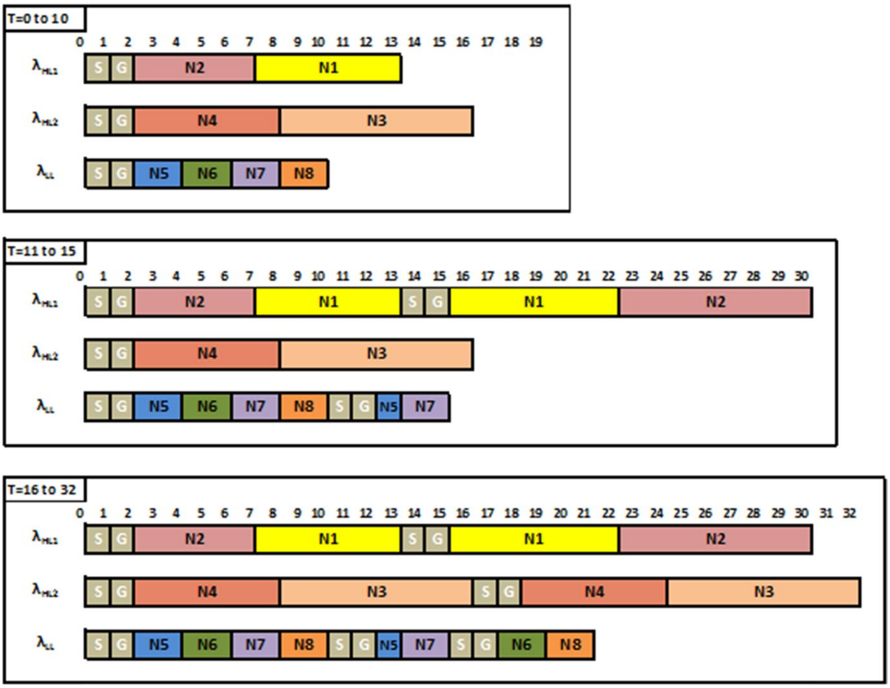

Fig. 7 Operational flow diagram of DWBA-II

ume of data the subscribers want to transmit towards OLT. DWBA-II is a cost effective solution that works on the principle of "pay as you grow".

- DWBA-I is based on the achievable system requirements of NG-EPON. DWBA-II is based on the achievable operational requirements of NG-EPON.
- DWBA-I is an algorithm for intra-ONU data/traffic transmission management on different wavelength channels. DWBA-II is an algorithm for inter-ONU data/traffic transmission management.
- DWBA-I is an algorithm that can provide quality-of-service based on different types of traffic. DWBA-II is an algorithm that can provide quality-of-service based on the cost of service.

5 Performance Evaluation

Our proposed DWBA-I and DWBA-II are comparatively evaluated and analyzed with the existing DWBAs by conducting a discrete event based simulation. Simulation is performed using NG-EPON model comprised of 64 ONUs and 4 wavelengths/channels for transmission of upstream traffic. ONUs are arranged in a tree shaped network arrangement connecting with central office OLT. All wavelengths of NG-EPON model are operating at a channel capacity of 25Gbps. Our network arrangement is segregated in two ONU groups with dissimilar traffic requirement. Group-1 covers the residential end-users with low traffic requirement and Group-2 comprises of corporate/business users with high traffic requirement.

Data requirements generated by corporate/business users would be 10 times greater than residential users. Difference in data traffic requirement between Group-1 and Group-2 is managed through different loads offered in our NG-EPON simulation. Ratio of traffic generated by ONU in per unit time at available number of wavelengths/channels to actual number of ONUs; referred as average load offered in NG-EPON. The above mentioned ratio is calculated as (4 × 25)Gb / 64). Our network load is assumed to be normalized and varies uniformly at different network loads offered in simulation. Buffer size for every ONU is considered to be 10 MB.

Fix guard time between consecutive grants is set to be 2 μs. Ethernet frames size distribution range is set from 64 to 1518 bytes. ONUs RTT is evenly distributed between a range 80–120 μs.

For DWBA-I simulation, we assigned one channel for LPT and three channels for HPT. We compared DWBA-I with EFT and EFT-VF. Comparison have been performed on the basis of average delay, completion time and packet drop ratio. In Fig. 8 shows comparison between DWBA-I and above given existing algorithms in terms of average packet delay (APD). Our DWBA-I improves APD comparatively to quite an extent. At lesser traffic loads, difference between APD of DWBA-I is smaller as compared to existing algorithm. At high traffic loads, the difference between proposed DWBA-I and EFT is higher, while the difference between DWBA-I and EFT-VF is lesser. Figure 9 shows comparison in terms of average completion time (ACT). Our proposed DWBA-I also performs better comparatively in terms of ACT. Figure 10 shows comparison of our proposed DWBA-I with EFT and EFT-VF in terms of packet drop ratio (PDR). Our DWBA-I also shows improvement on

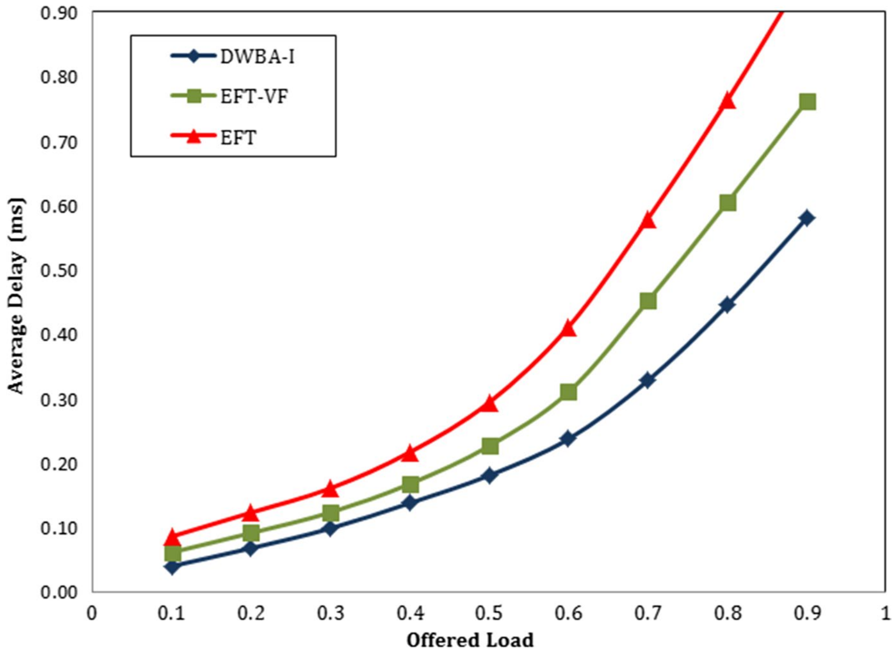

Fig. 8 APD comparison of EFT, EFT-VF and proposed DWBA-I

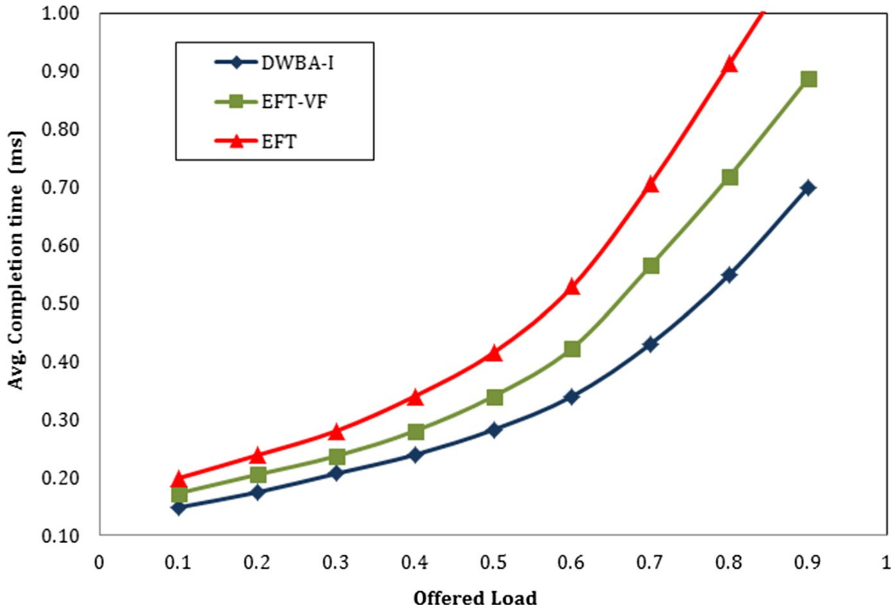

Fig. 9 ACT comparison of EFT, EFT-VF and proposed DWBA-I

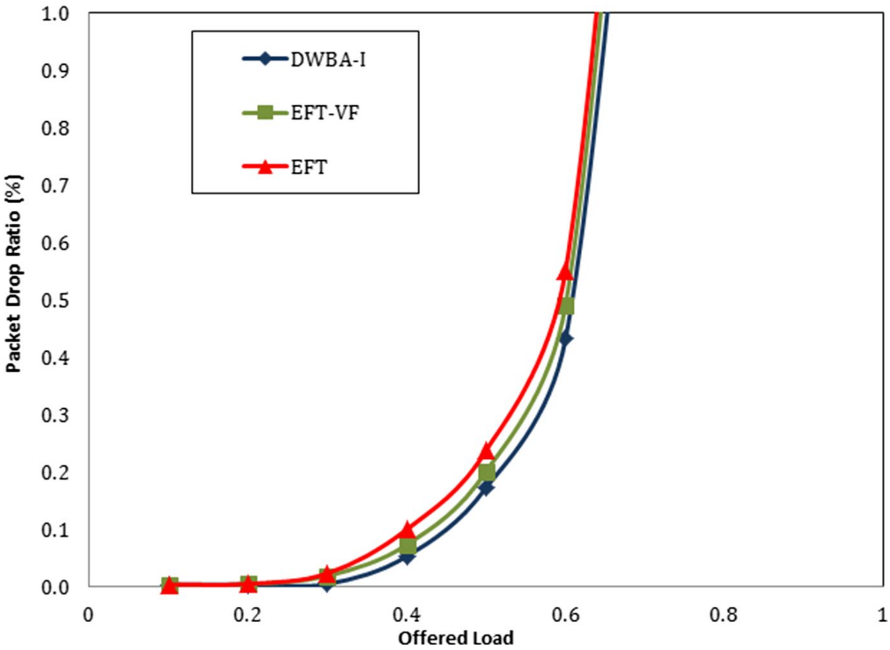

Fig. 10 PDR comparison of EFT, EFT-VF and proposed DWBA-I

the basis of PDR as compared to other two solutions. The simulation results show that our DWBA-I is better comparatively from EFT and EFT-VF according to above mentioned different network parameters.

We have allocated one wavelength for Light Loaded (LL) ONUs network traffic and three wavelengths for Heavy loaded (HL) ONUs network traffic for DWBA-II simulation. ONUs for residential subscribers are considered to be LL ONUs and ONUs for the corporate/business subscribers are considered to be HL ONUs. Comparison between DWBA-II with existing algorithms (i.e., First Fit-DWBA and Modified-IPACT-DWBA) have been performed in terms of APD, ACT, Grant Utilization (GU) and PDR. Figure 11 shows that our proposed DWBA-II performs better than Modified-IPACT and First-Fit in terms of APD. Our DWBA-II gives lower average packet delay at all offered loads. Comparative difference between our DWBA-II and two previous algorithms in terms of APD is higher at low network loads. At higher network loads, the gap in terms of average delay between our DWBA-II and other two algorithms decreases. In Fig. 12, comparison in terms of ACT is shown. Our proposed DWBA-II performs better in terms of completion time comparatively. Our proposed DWBA-II shows more improvement in terms of ACT at low traffic loads as compared to Modified-IPACT and First-Fit algorithms.

To evaluate performance of our proposed DWBA-II further, the comparison in terms of PDR is shown in Fig. 13. It is proved that DWBA-II performs better as compared to Modified-IPACT and First-Fit. Because of the improved fairness provided by our DWBA-II as compared to First-Fit and Modified-IPACT, the packet drop ratio is reduced. The performance of our proposed DWBA-II on the basis of

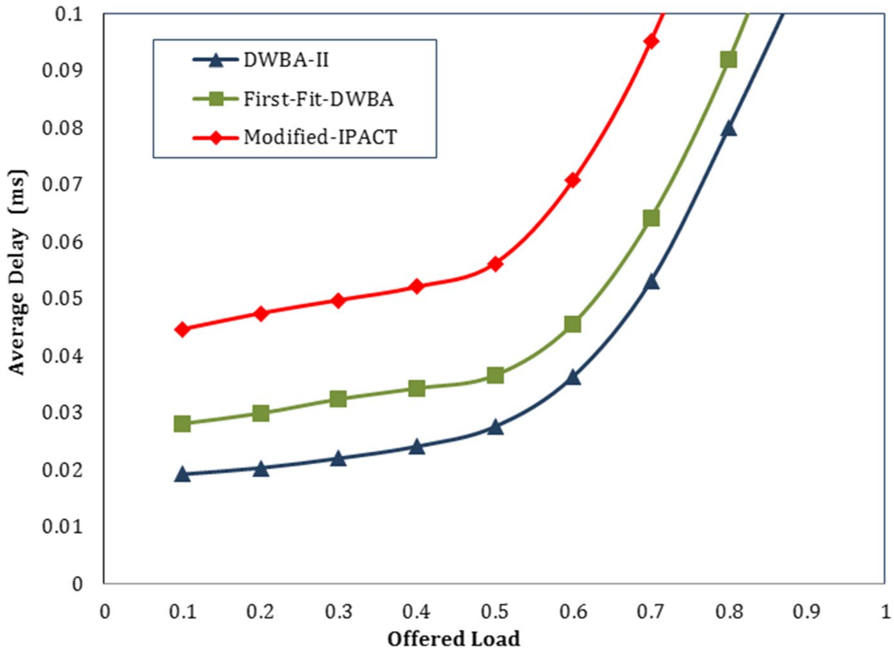

Fig. 11 APD comparison of Modified-IPACT, First-Fit and DWBA-II

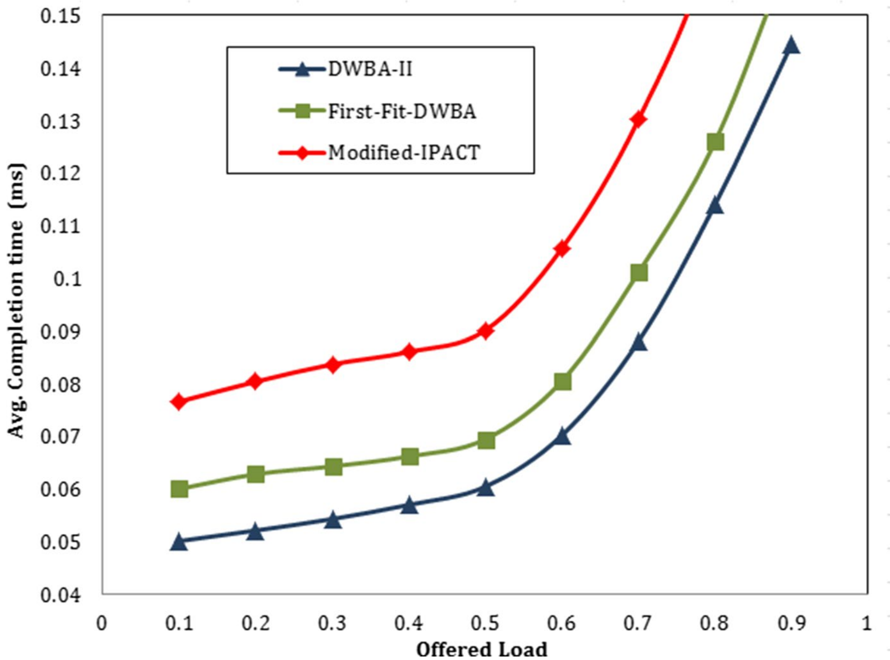

Fig. 12 ACT comparison of Modified-IPACT, First-Fit and proposed DWBA-II

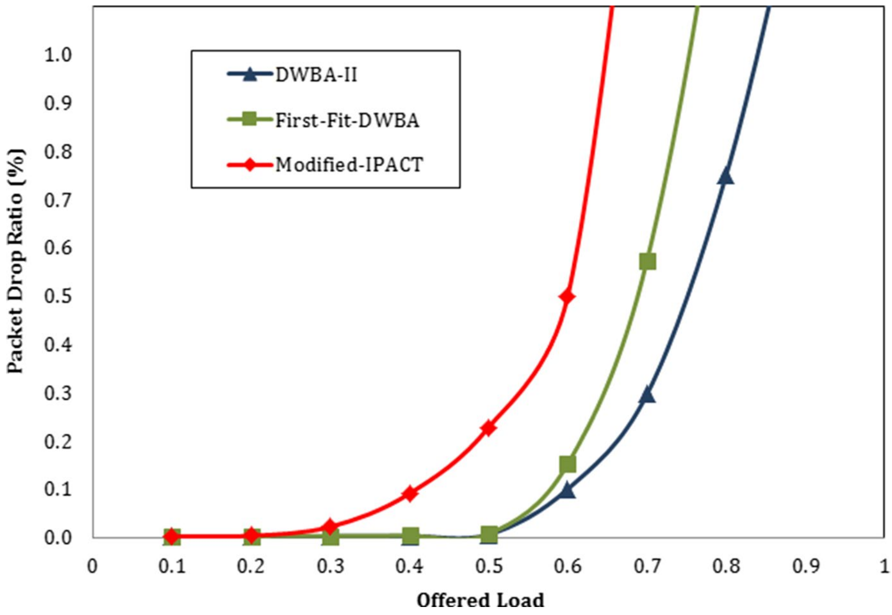

Fig. 13 PDR comparison of Modified-IPACT, First-Fit and DWBA-II

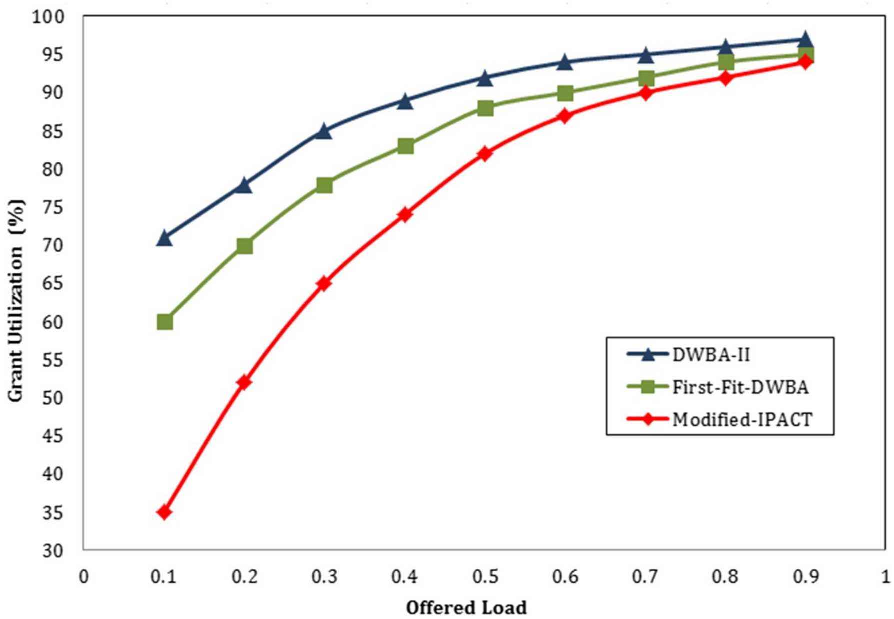

Fig. 14 GU comparison of Modified-IPACT, First-Fit and DWBA-II

grant utilization is shown in Fig. 14. It can be analyzed that our DWBA-II performs better in terms of channel utilization than First-Fit and Modified-IPACT. One of the reasons for decrease in delay in our proposed DWBA-II is the fact that two ONUs would be allocated a single wavelength channel for transmission one after the other; our Report to Schedule delay would be reduced to quite an extent as compared to other two existing solutions. Our proposed DWBA-II also avoids denial of packets transmission and size of packet mismatching problems; thus causes the reduction in bandwidth wastage as compared to other two DWBA algorithms. Moreover, our DWBA-II also avoids frame-resequencing issue at the OLT and thus no frame sequencing delay would be induced in NG-EPON execution.

6 Conclusion

A future access technology that could meet high capacity demand of subscribers for handling latest and up-to-date applications would be NG-EPON. For efficient bandwidth utilization in future access networks (NG-EPON), we proposed two different DWBA algorithms; DWBA-I and DWBA-II. Our proposed DWBA-I performs better as compared to existing algorithms by reducing the packet delays and packet drop ratio in NG-EPON. Simulation results verify that our DWBA-I performs better as compared to EFT and EFT-VF. In this paper, we also proposed a DWBA-II that improves bandwidth utilization as compared to Modified-IPACT and First-Fit algorithms. Our proposed DWBA-II reduces the Report to Schedule delay, avoids the bandwidth wastage and thus improves bandwidth utilization comparatively. In our DWBA-II, the overall delay would be decreased due to the reduction in report to schedule delay and avoidance of frames rearrangement delay. Our simulation results verify that our DWBA-II comparatively performs better than Modified-IPACT and First-Fit in terms of packet delay, packet drop ratio and grant utilization in NG-EPON.

References

1. Choi, S.Y., Lee, S., Lee, T.J., Chung, M.Y., Choo, H.: Double-phase polling algorithm based on partitioned ONU subgroups for high utilization in EPONs. J. Opt. Commun. Netw. **1**(5), 484–97 (2009)
2. Kabir, A., Rehman, G., Gilani, S.M., Kitindi, E.J., Ul Abidin Jaffri, Z., Abbasi, K.M.: The role of caching in next generation cellular networks: a survey and research outlook. Trans. Emerg. Telecommun. Technol. **31**(2), e3702 (2020)
3. Kramer, G., Mukherjee, B., Maislos, A.: Ethernet passive optical networks. IP over WDM: Building the next generation optical Internet. **1**, 229–75 (2003)
4. Yang, K., Ou, S., Guild, K., Chen, H.H.: Convergence of ethernet PON and IEEE 802.16 broadband access networks and its QoS-aware dynamic bandwidth allocation scheme. IEEE J. Select. Areas Commun. **27**(2), 101–16 (2009)
5. Gutierrez, L., Garfias, P., De Andrade, M., Cervelló-Pastor, C., Sallent, S.: Next generation optical access networks: From TDM to WDM. In: Trends in Telecommunications Technologies 2010. IntechOpen
6. McGarry, M.P., Reisslein, M., Maier, M.: WDM Ethernet passive optical networks. IEEE Commun. Magaz. **44**(2), 15–22 (2006)

7. Dhaini, AR., Assi, CM., Shami, A.: Quality of service in TDM/WDM Ethernet passive optical networks (EPONs). In 11th IEEE Symposium on Computers and Communications (ISCC'06) (2006) (pp. 616-621). IEEE
8. Bock, C., Prat, J.: WDM/TDM PON experiments using the AWG free spectral range periodicity to transmit unicast and multicast data. Opt. Expr. **13**(8), 2887–91 (2005)
9. Ranaweera, C., Wong, E., Lim, C., Nirmalathas, A., Jayasundara, C.: An efficient resource allocation mechanism for LTE-GEPON converged networks. J. Netw. Syst. Manag. **22**(3), 437–61 (2014)
10. Luo, Y., Yan, X., Effenberger, F.: Next generation passive optical network offering 40Gb/s or more bandwidth. In Communications and Photonics Conference (ACP), 2012 Asia (2012) (pp. 1–3). IEEE
11. Lam, C.F., Yin, S.: Evolution of fiber access networks. Optical Fiber Telecommunications VII, pp. 827–865. Academic Press, New York (2020)
12. Li, Z., Li, Y., Chen, J., Song, Y., Xu, T., Guo, Y., Yin, Y., Wang, M.: Requirements on Resolution and Sampling Jitter of ADC in 10G-Class Optics and MLSD based NG-EPON. In2017 Optical Fiber Communications Conference and Exhibition (OFC) (2017 Mar 19) (pp. 1-3). IEEE
13. Mohamed, I.M., Ab-Rahman, M.S.: Options and challenges in next-generation optical access networks (NG-OANs). Optik. **126**(1), 131–8 (2015)
14. Bindhaiq, S., Supa'at, A.S., Zulkifli, N., Shaddad, R.Q., Mataria, A.M.: Upgrade of an optical network unit in a 40 Gb/s time and wavelength-division multiplexed passive optical network using an upstream tunable colorless laser. Opt. Eng. **53**(7), 075107 (2014)
15. Mishra, V., Upadhyay, R., Bhatt, U.R., Kumar, A.: Wavelength-agile and radio-agile FiWi access network using dynamic scheduling to improve upstream delay and resource utilization. Heliyon. **5**(7), e02075 (2019)
16. Wang, W., Guo, W., Hu, W.: Dynamic wavelength and bandwidth allocation algorithms for mitigating frame reordering in NG-EPON. J. Opt. Commun. Netw. **10**(3), 220–8 (2018)
17. Radzi, NA., Din, NM., Sadon, SK., Al-Mansoori, MH.: Dynamic bandwidth allocation EPON survey. In 2013 IEEE Student Conference on Research and Developement (2013) (pp. 149–153). IEEE
18. Bhatia, S., Garbuzov, D., Bartos, R.: Analysis of the gated IPACT scheme for EPONs. In2006 IEEE International Conference on Communications (2006 Jun 11) (Vol. 6, pp. 2693–2698). IEEE
19. Buttaboni, A., De Andrade, M., Tornatore, M., Pattavina, A.: Dynamic bandwidth and wavelength allocation with coexisting transceiver technology in WDM/TDM PONs. Opt. Switch. Netw. **1**(21), 31–42 (2016)
20. Segarra, J., Sales, V., Prat, J.: OLT design approach for resilient extended PON with OBS dynamic bandwidth allocation sharing the OLT optical resources. In Transparent Optical Networks, 2008. ICTON 2008. 10th Anniversary International Conference on (2008) (Vol. 4, pp. 139-144). IEEE
21. Ragheb, AM., Fathallah, H.: Performance analysis of next generation-PON (NG-PON) architectures. In8th International Conference on High-Capacity Optical Networks and Emerging Technologies (2011) (pp. 339–345). IEEE
22. Dhaini, AR., Assi, CM., Shami, A.: Dynamic bandwidth allocation schemes in hybrid TDM/WDM passive optical networks. InProc. IEEE CCNC (2006) (Vol. 6)
23. Buttaboni, A., De Andrade, M., Tornatore, M.: A multi-threaded dynamic bandwidth and wavelength allocation scheme with void filling for long reach WDM/TDM PONs. J. Lightwave Technol. **31**(8), 1149–57 (2013)
24. McGarry, M.P., Reisslein, M., Colbourn, C.J., Maier, M., Aurzada, F., Scheutzow, M.: Just-in-time scheduling for multichannel EPONs. J. Lightwave Technol. **26**(10), 1204–16 (2008)
25. Ni, C., Gan, C., Li, W., Chen, H.: Bandwidth allocation based on priority and excess-bandwidth-utilized algorithm in WDM/TDM PON. AEU Int. J. Electron. Commun. **69**(11), 1659–66 (2015)
26. Hussain, SB., Hu, W., Li, C.: Fair DWBA for WA-PON based NG-EPON (100G-EPON) to mitigate frame resequencing problem. In2017 Opto-Electronics and Communications Conference (OECC) and Photonics Global Conference (PGC) (2017) (pp. 1–2). IEEE
27. Hussain, S.B., Hu, W., Xin, H., Mikaeil, A.M.: Low-latency dynamic wavelength and bandwidth allocation algorithm for NG-EPON. J. Opt. Commun. Network. **9**(12), 1108–15 (2017)

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