Dynamic Hybrid-Slot-Size Bandwidth Allocation Algorithm for Improving Quality of Services of Real Time Traffic in Ethernet Passive Optical Network (EPON)

By

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Declaration

This is to certify that the thesis work entitled "*Dynamic Hybrid-Slot-Size Bandwidth Allocation Algorithm for Improving Quality of Services of Real Time Traffic in EPON* " has been carried out by *Md. Selim Morshed* in the Department of Electronics and Communication Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

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Approval

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Abstract

In the modern data networks, users are communicating via real time traffic, i.e., high priority (HP) traffic, very often. The demand is increasing for interruption free, high speed, high efficiency, and best quality of services to perform successful communications. This thesis emphasizes on the HP traffic like video conferencing, video chat, telemedicine, teleconferencing, and interactive gaming for the real time communication. In contrast, the low priority data is considered as the best effort (BE) traffic because the BE traffic do not require delay sensitive applications.

To achieve better quality data communication for the HP traffic, Ethernet passive optical network (EPON) is used to fulfill the bandwidth demand of such real time traffic. The effectiveness of EPON mostly depends on dynamic bandwidth allocation (DBA) algorithm. In this thesis, we propose a new DBA algorithm called dynamic hybrid-slot-size bandwidth allocation (DHSSBA) algorithm. To ensure better performance, the proposed DHSSBA is also incorporated with the new multi-point control protocol (MPCP). As the DHSSBA scheme uses two Gate messages, one Gate message for the HP traffic and other one for the BE traffic, for each optical network unit (ONU) in a time cycle, the proposed MPCP protocol eliminates the synchronization problem between the two Gate messages. The performances of the proposed scheme are also compared with the existing hybrid-slot-size/rate (HSSR) scheme and delay variation guaranteed polling (DVGP) scheme. The performance of the proposed scheme has been analyzed by using numerical simulation in terms of the end to end packet delay, jitter variation and throughput for both the HP and BE traffic. From the comparison of the simulation results it is clear that the proposed scheme provides lesser end to end packet delay for the HP traffic and provides better performances than those of the HSSR and DVGP schemes.

Keyword: DBA Algorithm, DHSSBA, HSSR, DVGP, High Priority traffic, Best Effort traffic.

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Author

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List of Abbreviations

AF	Assured Forwarding
APON	ATM Passive Optical Network
ATM	Asynchronous Transfer Protocol
BE	Best Effort
BPON	Broadband Passive Optical Network
CATV	Cable TV
DBA	Dynamic Bandwidth Allocation
DSL	Digital Subscriber Line
DVGP	Delay Variation Guaranteed Polling
DHSSBA	Dynamic Hybrid-Slot-Size Bandwidth Allocation
EF	Expedited Forwarding
EPON	Ethernet Passive Optical Networks
FSAN	Full Service Access Network
FTTB	Fiber-to-the-Building
FTTC	Fiber-to-the-Curb
FTTH	Fiber-to-the-Home
GPON	Gigabit Passive Optical Network
HP	High Priority
HDTV	High Definition Television
HSSR	Hybrid Slot-Size/Rate
IEEE	Institute of Electrical and Electronic Engineering
IPTV	Internet Protocol Television
IPACT	Interleaved Polling with Adaptive Cycle Time
ITU-T	International Telecommunications Union Telecommunication Standardization Sector
LAN	Local Area Network

MAN	Metropolitan Area Network
MPCP	Multi-Point Control Protocol
OFDM-PON	Orthogonal Frequency Division Multiplexing-Passive Optical Network
OLT	Optical Line Terminal
OPEX	Operational Expenditure
ONU	Optical Network Unit
P2MP	Point-to-Multi-Point
P2P	Point-to-Point
PON	Passive Optical Network
POS	Passive Optical Splitter
QoS	Quality of Service
SBA	Static Bandwidth Allocation
SLA	Service Level Agreement
SONET	Synchronous Optical Network
SDH	Synchronous Digital Hierarchy
TDM	Time Division Multiplexing
TDM-PON	Time Division Multiplexing-Passive Optical Network
VoD	Video on Demand
WDM-PON	Wavelength Division Multiplexing–Passive Optical Network

CHAPTER I

INTRODUCTION

This chapter begins with an overview of the developments in access networks. Then passive optical network (PON) with its history, technologies, standard and applications are discussed sequentially. The motivation and contributions of this research work is presented analytically at the end.

1.1 Overview of the Access Networks

An access network is a part of telecommunication network which is used to deliver voice, video or data services using copper cables, optical fibers, wireless links or a combination of both such as copper cables and optical fibers [1]. Fig. 1.1 shows the diagram of the access network. Remote node in the access network plays a vital role by connecting last mile with feeder medium to accumulate or distribute data between end users and local exchange.

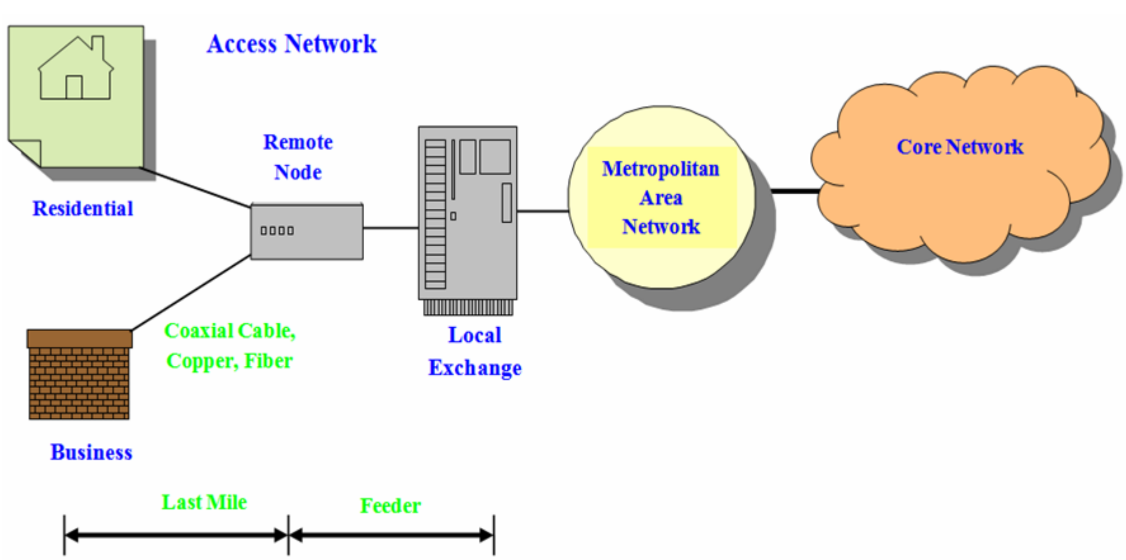

Fig. 1.1 An example of access, metropolitan and core networks.

Basically the central office (CO) is referred as the local exchange acts as a gateway to metropolitan network. A large number of the COs are connected to each other using optical fiber mostly form ring topology.

It delivers customer's voice, video and data services from tens to hundreds of kilometers and finally the metropolitan network connects to the core network router which in the form of mesh topology interconnects cities or regions over the distances of hundreds to thousands of kilometers [2].

Previously point to multi-point (P2MP) network topologies were used to deliver broadband connectivity, but now wireless and wire line alternatives are using as the current access network technologies in that purpose [3]. Wireless interoperability for microwave access (WiMAX) [4] and wireless fidelity (WiFi) [5] can deliver 70 Mbps connections for distances of 5 km and 50 Mbps connections for up to 100 meters, respectively. However, they have some limitations to support high-speed internet and media-rich video applications as only a few new products developed to incorporate the WiMAX and tens to hundreds of users are sharing the available bandwidth [3, 6]. Alternatively, digital subscriber line (DSL) over copper provides another point-to-point access wire line technology option to deliver 24 Mbps in the downstream using its flavor such as asymmetric DSL2plus (ADSL2plus) [7]. But the effective bandwidth for each subscriber is limited according to the local loop length because of noise problems at high frequencies [3].

For example, to allow subscribers to receive compelling internet and video services at 30 Mbps in the downstream with 1 Mbps upstream capability, local loop length must be decreased to approximately 1000 meters [3]. The standardization of second-generation very-high-bit-rate DSL2 (VDSL2) is regulated in ITU-T G.993.2 to accommodate real time access and increase the network reach [8]. This is achieved by using large bandwidth pipelines at close proximity to subscribers through replacement of feeder part of the network with optical fibers resulting to hybrid fiber-copper access networks capable for delivering more than 50 Mbps data rate in downstream directions [8].

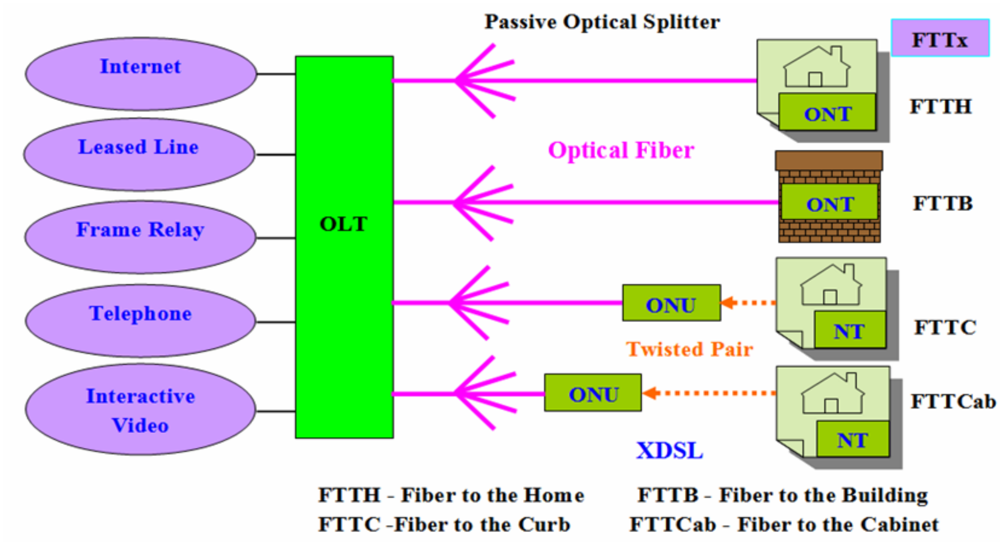

Fig. 1.2 Fiber to the X-architectures [10].

In the range of about 100 meters, the maximum available bit rate can be achieved [3]. With reference to the fiber-to-the-curb/cabinet (FTTC) architecture as shown in Fig. 1.2., the fiber in VDSL2 applications could be terminated at an optical network unit (ONU) which is located in a street cabinet, from where twisted pair copper lines extend it to the customer ends. However, to meet the increasing bandwidth demand, fiber connectivity all the way to customer can be the ultimate solution, makes it ideal candidate to meet the capacity challenges in the foreseeable future. Besides this, fiber-to-the-home (FTTH) architectures have been extensively investigated and standardized as the demand for high-speed access network is increasing rapidly [9].

According to the international telecommunication union–telecommunication (ITU-T) standardization sector's full-service access network (FSAN) group [11-13], to provide triple-play services, the advised downstream bandwidth for a single residential customer is 73 Mbps including three high-definition television (HDTV) channels (3×20 Mbps), high-speed internet access (10 Mbps), video-conferencing (2 Mbps) and telemetric/remote control (1 Mbps) [14,15] as summarized in Table 1.1.

Table 1.1 Bandwidth estimation for a single residential customer [16].

Service	***Bandwidth***	***Comments***
Three HDTV channels at 20 Mbps per residential	60 Mbps	Three HDTV channels
Internet, Education-on-demand, online gaming	10 Mbps	Peer-to-peer require symmetrical bandwidth
Video conference of video phone	2 Mbps	Requires symmetrical bandwidth
Remote control, sensing	1 Mbps	Requires symmetrical bandwidth
Total	**73 Mbps**	**Downstream: 73 Mbps** **Upstream: 53 Mbps**

Symmetrical bandwidth services in the upstream direction including online gaming, video-conferencing and education-on-demand in tandem with high-speed internet and other services are expected to necessitate up to the 53 Mbps bandwidth [16]. In the near future, the required symmetrical bandwidth for a single residential customer or small business is expected to be increased up to 100 Mbps by considering services like remote backup and Web 2.0 applications etc. [17].

The applications of the FTTH or the business premises technologies have achieved considerable support from incumbents because it can meet these capacity challenges in the access network in the foreseeable future [2]. The Ethernet based FTTH technologies have been extensively investigated and standardized due to widespread adoption of the Ethernet protocol in local area networks [3, 9]. To start with Gigabit Ethernet, customers access their local exchange at hundreds to thousands Mbps through P2P full-duplex fiber connections with an Ethernet router/switch deployed in a street cabinet. To place an active device in the street cabinet would require high operational expenditure (OPEX) due to the need of electrical power provisioning and monitoring as well as maintenance of backup batteries [18]. Since the network architecture is not transparent to various signal formats and data rates, so to meet the demand of increased data rates and transmission protocols, street cabinet electronics would need to change [3].

On the other hand, the PON technologies with its passive optical devices like passive splitters can connect the optical line terminal (OLT) in the local exchange with multiple residential and business customers providing simplicity and extended reach bandwidth in access network architectures [3, 19]. Since there is no need to maintain active components operation as well as to avoid malfunctions, the PON are expected to maintain very low OPEX. For agnostic nature of the passive splitter, a PON-based access network comprises with optically transparent end to end and capable of supporting various protocols, increasing data rates and additional wavelengths with no alterations in hardware. In addition, service providers are challenged with deploying access solutions that are scalable, fast, and cost effective to ensure their competitive positions. The PON technology can address these needs through the use of optical fibers in place of the traditional copper wire and it is also a very practical solution in eliminating the bottleneck in access networks [1, 16, 19-22].

1.2 Passive Optical Network

A PON is a point-to-multipoint, fiber to the premises network architecture in which optical splitters are used to enable a single optical fiber to serve multiple premises, typically 16-128. A PON is a data link access technology that delivers data from OLT to optical network units (ONUs). The OLT is located at the service provider's CO and a number of ONUs are located at the near end users. A PON reduces the amount of fiber and CO equipment required compared with point to point architectures [23]. It is a highly capable access network providing numerous advantages to the several service providers without any bandwidth problem. The PON is considered as a promising next-generation access technology to fulfill the high bandwidth demand by the real time data traffic. It is an efficient access network that provides lower operation and maintenance costs and allows larger distance between the CO and end users [24].

1.3 History of the Passive Optical Network

In 1980, when the optic technologies [25-26] was at the beginning of their evolution and just used in long haul communication systems, the PON technology was introduced. In this period, fiber has found lots of place in telecommunication companies' core, backbone and metro networks. In 1990s, the increase of bandwidth demand of end users paves the way for using optical fiber lines to be used as an access network solution. This opened the way for the standardization studies. One of the main events for development of PONs is the foundation of "full service access network" (FSAN) working group.

At the start of its study, the FSAN group has decided to use PON topology and "time division multiplexing/multiple access (TDM/TDMA)" in access solutions. In 1996, the FSAN consortium decided asynchronous transfer mode (ATM) is the best encapsulation method in multi service networks. This decision has formed the first PON standard. This standard has accepted and presented by the ITU-T as a full recommendation under (ITU-T Rec. G.983.1, 2005). This first standard is known as ATM PON (APON).

Nippon telegraph and telephone (NTT) company used the APON to deliver broadband access on whole Japan. At this period, in USA some service providers perform limited experiments or deployments. Besides Verizon and southwestern bell communications (SBC) (now part of AT&T) used APON in business approaches and improvements of cooper telephony systems. In this period, the PON seems to be expensive compared to novel synchronous optical network (SONET) based platforms.

At the end of 1990s, the PON ripens [27] as a mature technology to implement. However, for the business especially in USA and Europe, the PON applications were pushed back for some reasons. First reason is that the capital expenditure is still too high for that day, second reason is the necessity of bandwidth supported by fiber lines is much higher than the demand, and third reason is the ambiguity in the industry as governments have not approved the standards. By this moment, cable television (TV) systems are not capable to give three play services. Thus service providers head towards to the xDSL systems. There was a little exception like FTTC implementation for new buildings by Bellsouth company.

Since APON proved itself as an optimistic solution for access, its users (NTT and Bellsouth) have known that it is inadequate and has to be developed [28]. As a result of that, broadband PON (BPON) systems developed as an improvement to APON. The BPON is developed by the requirement analysis of the FSAN and written under the ITU-T G.983 standards series. In this standard, 622Mbps downlink and 155Mbps or 622Mbps uplink transmission speed. Each CO unit/OLT has a reach up to 32 users at 20km. The BPON also uses TDM mechanism and ATM packaging. Since, BPON seems an upgrade to APON and mostly call with the same name. BPON used by three companies in USA from 2003 to 2007.

In March 2001, the working [29] group 802.3 in IEEE consortium started 802.3ah "Ethernet in the first mile" (EFM) project. The main aim was to use Ethernet frames in the PON systems. IEEE adopted a technology based approach contrary to FSAN/ITU's approach. The key idea was a PON system must use Ethernet frames from the connected local network with a small arrangement on packets. By this means EPON turns to the best access network solution to carry the best effort (BE) internet traffic. In June 2004, IEEE 802.3ah's EPON standard was approved. EPON was standardized as capable to serve 16 ONUs over 10 - 20km. The EPON was commercialized by chance because of NTT's need to struggle other service providers to give favorable bandwidth. Since, the EPON gained much more interest in the East Asia region.

Meanwhile the EPON standard was developed, FSAN/ITU were working on a novel PON standard, Next Generation PON (NG-PON). First studies were on ATM structure, then Ethernet packaging was used. At last, physical layer packaging was adopted (like Generic Framing Procedure in SDH/SONET). This study was standardized under G.984 standard document and named as gigabit capable PON (GPON). For transmission "generic encapsulation method" or "GPON encapsulation mode" (GEM) was used, and bandwidth capacity on downlink had increased 2.5Gbps and capacity on uplink to 1.25Gbps.

In 2007, IEEE 802.3av [30] workgroup was founded to develop 10Gbps EPON (10G EPON) systems. This work adopted two ideas such as; 10Gbps downlink with 10Gbps uplink capacities and 10Gbps downlink with 1Gbps uplink capacity working systems. They specified that asymmetric infrastructures were sufficient for near future needs. The desired use case was to support 10Gbps up/down symmetric capacity. The IEEE 802.3av workgroup finalized their studies and published the standard in September 2009, IEEE Standard for information technology 802.3av 2009. In 10G-EPON, wavelengths were selected to allow backward compatibility to allowing coexistence of 1G-EPON and RF video transmission. Since 802.3av was working on 10G-EPON, the FSAN group was working to develop their new standardization named as NG-PON.

On the road of the NG-PON, in 2010, the ITU-T published next version of GPON named as XG-PON (ITU-T Rec. G.987 series, 2010). The XG-PON extends the GPON standard as 10Gbps downstream and 2.5Gbps upstream capacities. It also allowed coexistence with the GPON. The XG-PON did not bring to much improvement in terms of split ratio and target distance. For these improvements, the next step was thought to include wavelength division multiplexing (WDM) to go beyond the XG-PON.

This decision illustrated the NG-PON strategies. The FSAN consortium was developing ideas on multiple enhancement systems. While the XG-PON was suitable for backward compatibility, NG-PON seems to be unavailable for coexisting of old standards. In NG-PON, besides, the ITU-T 15 and IEEE 802.3 working groups agreed to exchange the ideas for new PON standard development. This was expected to allow [31] next generation products to work with less conformity problems.

The WDM-PON was [32] seen to be solution for next generation access and backhaul networks. The WDM-PONs has the advantages such as; scalable bandwidths, access to long haul, ability to give different bandwidth capacity on different wavelengths. These benefits make the WDM-PON a suitable solution to use mutually for home, business access, and backhaul networks. Thus, the WDM-PON is highly discussed in recent researches. Since home users do not need more than 1Gbps bandwidth capacity, WDM-PON systems are expensive solutions compared to EPON and GPON systems.

Besides, wavelength division limits obstruct the expansion. By sharing each wavelength among subscribers, the cost can be decreased and much more subscribers can be reached (as 1:500 division rates). These values can be available by using each wavelength by a number of subscribers, e.g., in a dense wavelength division multiplexing PON (DWDM-PON), the 40th

wavelength each is separated as 1:8 or 1:16. By keeping the separation ratio lower than EPON /GPON values, the bandwidth given per user can be increased.

In Korea, between 2003 and 2006, ETRI and Novera [33] developed the WDM-PON systems that have 16 wavelengths and 1.25Gbps up/down link capacity. In 2007, Korea telecom (KT) used first burst mode transceiver (BMT) and in March 2008 second one was achieved. Since April 2008, KT used the WDM-PONs developed by ETRI to give broadband access service. Besides, in Korea hybrid solutions such as WDM TDM-PON and long reach WDM-PON were under development with government supported projects.

In 2012, Green Touch consortium released Bit Interleaved PON [34] while it has the same equipment with XGPON, the running protocol has changed. BiPON protocol is constructed on the fact that over ninety percent of the traffic processed in ONUs is unnecessary.

1.4 PON Technologies

1.4.1 TDM- PON

Two types of TDM PONs such as GPON and EPON are now widely accepted as optical access network solutions, by using optical fiber network infrastructure they are used to distribute reasonably high bandwidth to the customers. Fig. 1.3 shows a tree topology based TDM-PON architecture. In TDM technique, a single wavelength channel is shared by all the users attached to a TDM-PON, the average dedicated bandwidth normally limited to a few percent of the channel capacity, i.e., a few tens of Mbps is assigned to each user in either directions. Because of lower maintenance costs and more reliable operation network operators tend to support the TDM-PON scheme. The TDM-PON architecture provides only limited scope for improving the bandwidth performance because the whole ONUs in the network shared the bandwidth that is provided by one wavelength [24].

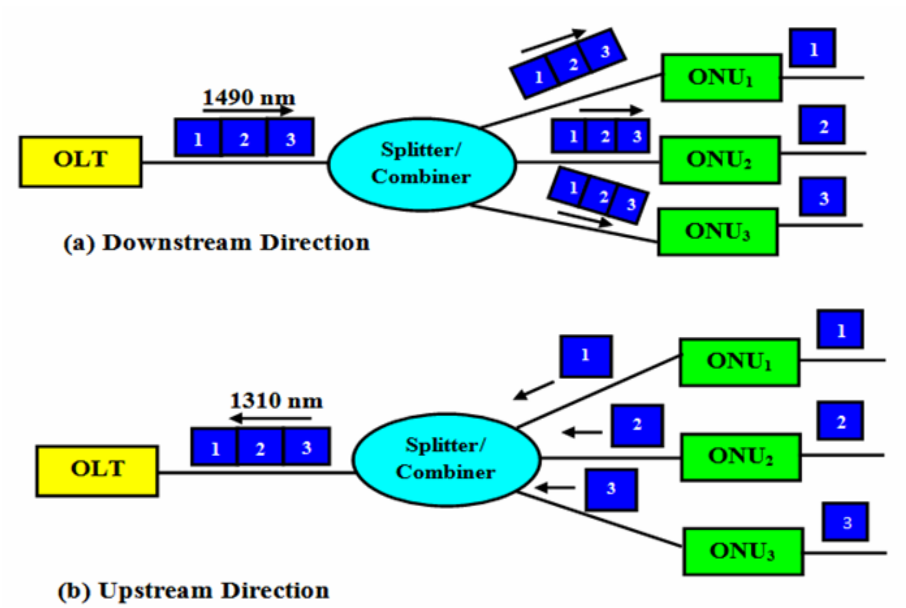

Fig. 1.3 TDM-PON architecture [24].

1.4.2 WDM-PON

In the WDM-PON architecture, all the ONU can transmit data independently since each optical network unit is assigned its own dedicated wavelength. The WDM-PON is comprised with high data bandwidth, scalability and enhanced security to support several local subscribers. Technologies like Wireless Fidelity, Wireless Interoperability for Microwave Access, and 3rd Generation are becoming popular for their scalability and flexibility. Many WDM-PON designs are proposed. Within this, the WDM-PONs are deployed as tree topology or bus topology with its characteristic of simplicity and flexibility which is shown in Fig. 1.4. In the WDM-PON, a dedicated pair of wavelengths is assigned to each ONU; hence, high-bit-rate transmission in both upstream and downstream directions can be easily guaranteed for each ONU. The WDM-PON also provides a direct optical point-to-point link between each ONU and the OLT. Hence, there is no need to handle complicated PON over network management and Ethernet mapping. WDM-PON systems have several advantages over conventional TDM-PON systems. Firstly, each user in the WDM-PON is dedicated with one or more wavelengths, providing each subscriber to access the full bandwidth accommodated by the wavelengths. Secondly, as each user only receives its own wavelength in the WDM-PON providing scalability and better safety [24].

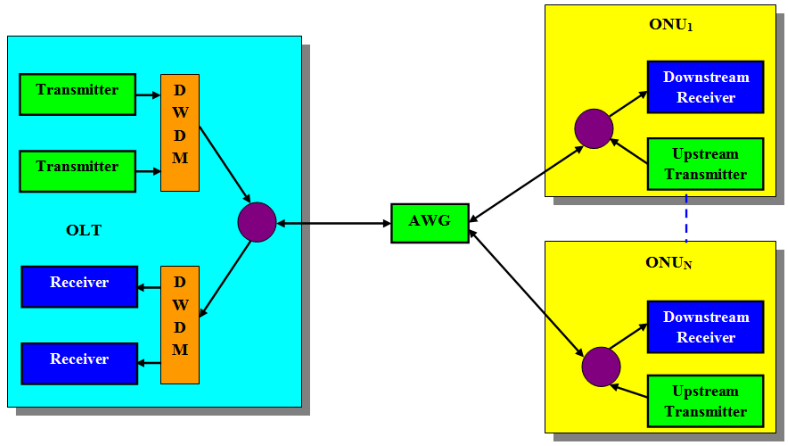

Fig. 1.4 WDM-PON architecture [24].

1.4.3 OFDM- PON

Orthogonal frequency division multiplexing PON (OFDM-PON), as shown in Fig. 1.5., employs OFDM as the modulation scheme and exploits its superior transmission capability to improve the bandwidth provisioning of optical access networks. In OFDM, a large number of closely spaced orthogonal sub-carriers are used to carry data traffic. For achieving the sum of the rates provided by all sub-carriers compatible to those of predictable single-carrier modulation schemes in the same bandwidth, this conventional modulation scheme is used to modulate each sub-carrier at a low symbol rate. The duration of each symbol is relatively large because the data rate carried by each sub-carrier is low. As a result, the inter-symbol interference (ISI) can be efficiently reduced in a wireless multi-path channel. Therefore, employing the OFDM modulation scheme in the optical access network can greatly increase the network provisioning data rate and extend the network. Since the OFDM frames can realize two dimensional resource allocations in both the time and frequency domains, for that reason, the OFDM-PON is flexible. However, due to optical interference effect, resource allocation in frequency domain for different ONUs will induce severe fluctuation [24]. Fig.1.5 shows the OFDM-PON architecture.

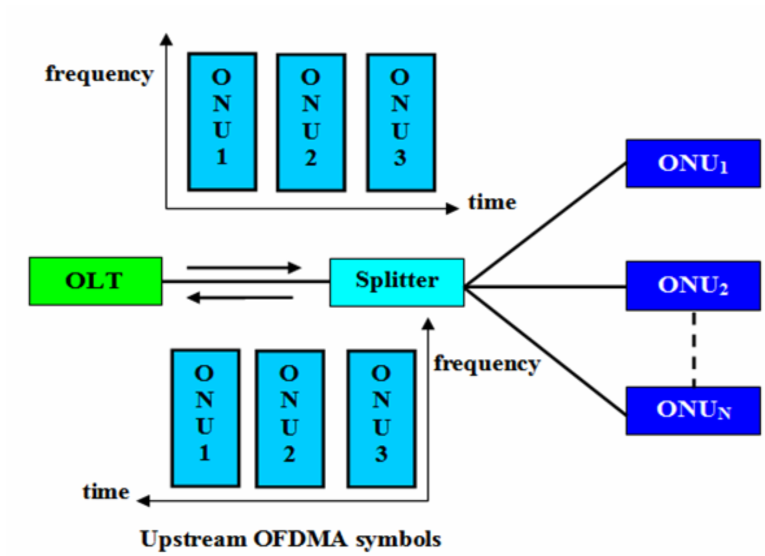

Fig. 1.5 OFDM-PON architecture [24].

1.5 PON Standard

The PON technology has been available from the mid-1990s. To develop Gigabit rate solutions used to provide Ethernet and IP services, significant development activities has been occurred during the early 2000s. The IEEE and ITU-T developed EPON and GPON- two very different solutions, respectively. The EPON and GPON have some features and services, within this the general concepts like PON operation, ODN framework, wavelength plan, and application are the same for both of them but their operation is different. EPON is a native Ethernet solution that leverages the features, compatibility and performance of the Ethernet protocol, while GPON leverages the techniques of SONET/SDH and generic framing protocol (GFP) to transport Ethernet.

The PON standardization activities have been ongoing for the past fifteen years within the ITU-T and IEEE standards bodies. EPON and 10G-EPON are the latest ratified IEEE standards and GPON is the latest ratified ITU-T standard [35]. Fig. 1.6 shows some of the key historical milestones:

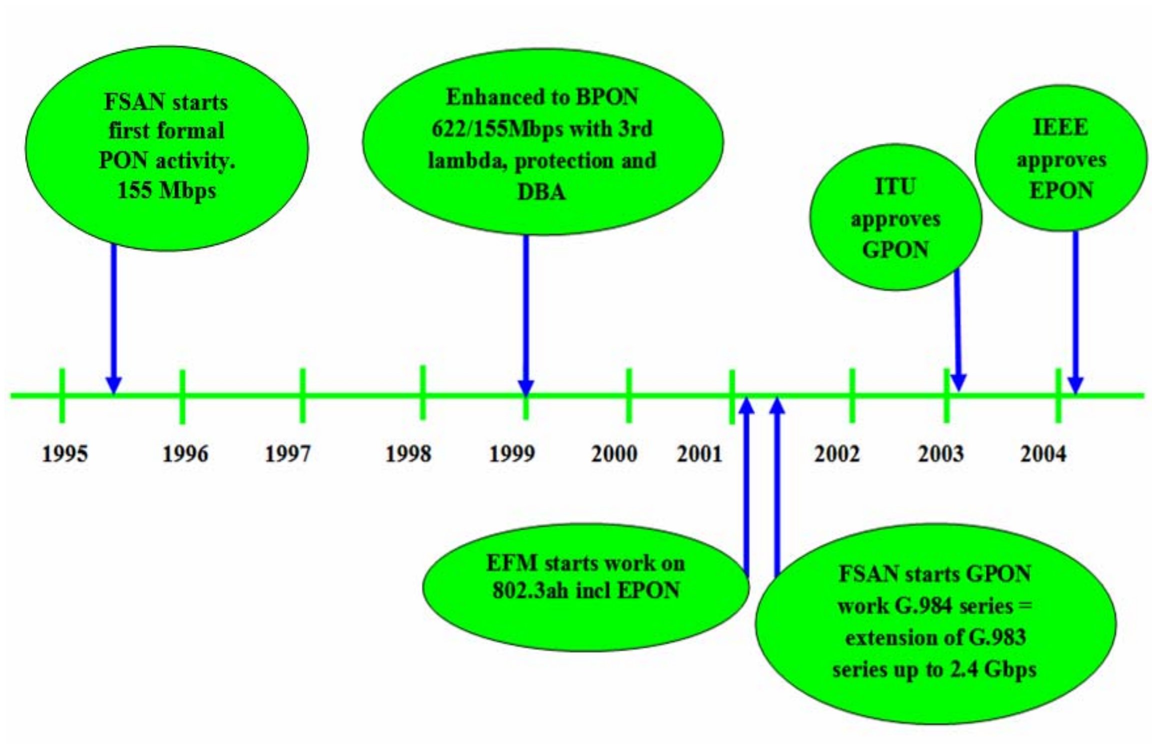

Fig. 1.6 PON standard.

Initial PON offerings in the early and mid-1990s were based on ATM framing, i.e., APON and BPON. With the explosion of internet and intranet-based traffic in the years following, ATM-based BPON systems proved to be very inefficient, as the vast majority of traffic through the access network consisted of variable-length IP traffic. This became the catalyst for the development of a purely Ethernet-based PON (EPON), taking advantage of emerging QoS-aware gigabit Ethernet (GbE) switch silicon, evolving Ethernet standards (VLANs, prioritization, OAM), and cost-effective integration with other Ethernet equipment.

Development of the GPON standard started after proposals by FSAN members (Quantum Bridge et al) for a dual Gigabit speed ATM/Ethernet PON solution were not able to gain support within the IEEE 802.3ah work groups and decided to continue this work within the ITU [35].

1.6 Application of PONs

In terms of the functionality, the PONs are categorized [24] into three areas:

(i) Broadband Internet Application

(ii) Triple Play with RF Video

(iii) IP Triple Play Application

1.6.1 Broadband Internet Application

In Japan, FTTH started from simple application of IP/Ethernet and it is still leading. Simple indoor ONU provides broadband access of 100 Mbps best effort service. Fig. 1.7 shows typical broadband Internet architecture. The service is like of ADSL.

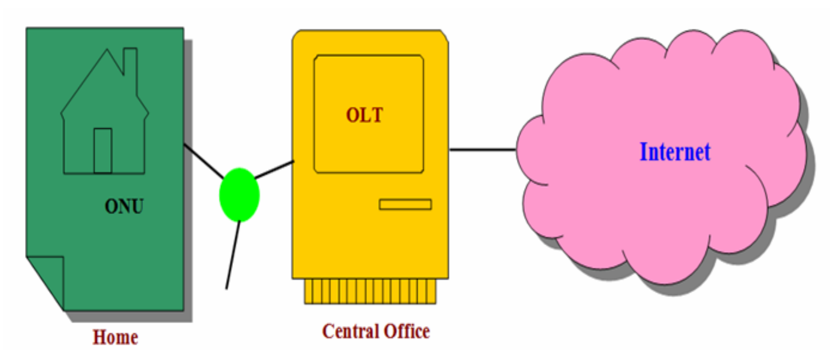

Fig. 1.7 Broadband Internet.

1.6.2 Triple Play with RF Video

Using the WDM radio frequency overlay provides conventional CATV type video service in addition to broadband internet as shown in Fig.1.8. This application is very popular in North America.

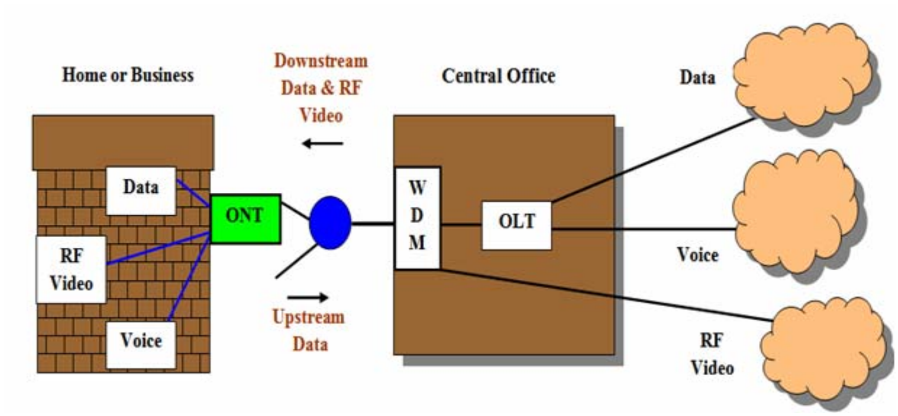

Fig. 1.8 Triple play with RF video.

1.6.3 IP Triple Play Application

Home gateways are used to separate the IP video and provide plain old telephony service (POTS), conversion as shown in Fig.1.9. Entire network based on IP and Ethernet.

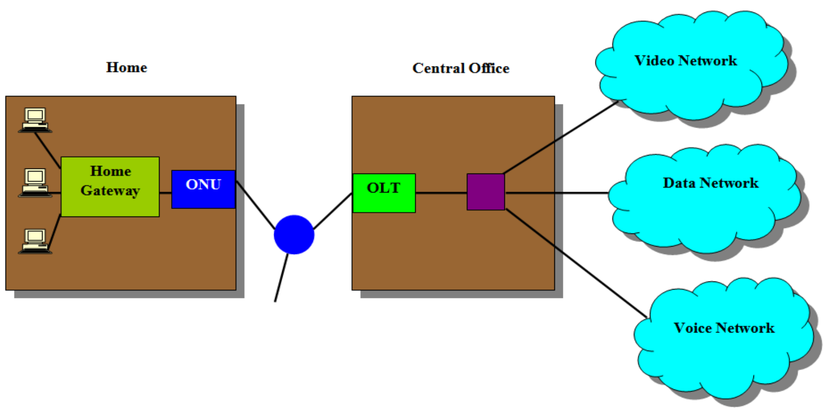

Fig. 1.9 IP triple play application.

1.7 Motivation and Contributions of the Research

1.7.1 Motivation

We are in the age of telecommunication where Internet is an important issue and it is a network of networks that acts as not only a single telecommunication infrastructure but also as a system that combines many telecommunication infrastructures. Most of the service providers use optical network infrastructures to provide optimal solution of Internet demanding high bandwidth capacity because users in the video-centric world are communicating via Internet are mostly interested with real time traffic like video conferencing, high quality online game, video chatting , Internet protocol television, high definition television, video on demand, video surveillance etc. These types of bandwidth hungry services need interruption free high speed communication. This leads the service providers to support high bandwidth in the access network. EPON is the classical implementation of the PON and needs proper DBA.

1.7.2 Contributions, Problem Statement and Functional Component

The contribution of this thesis work is to reduce the packet delay of above mentioned real time traffic which we considered the high priority (HP) traffic as well as improve jitter performance and throughput. So, our goal is to develop a dynamic hybrid-slot-size bandwidth allocation (DHSSBA) algorithm in EPON to fulfill the above mentioned requirements and compare it with previously developed hybrid slot-size/rate (HSSR) bandwidth allocation algorithm and delay variation guaranteed polling (DVGP) scheme then evaluates the performance of both the existing schemes with the proposed scheme to prove the proposed scheme better than the reference schemes.

1.8 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 represents the literature review where at the very beginning, EPON and GPON are compared with respect to protocol fundamentals, framing/service adaptation, service hierarchy, DBA of EPON and GPON, bandwidth allocation, control messages, ONT discovery and activation, encryption, Ethernet service support, bridging, transparent LAN services (TLS), reach, per subscriber cost, usable bandwidth, efficiency, management system, support for CATV overlay and network protection. Then EPON general structure is described. Then importance of DBA scheme is discussed and some DBA algorithms of the EPON are examined.

Chapter 3 represents procedure/methodology where at first, the EPON architecture in the proposed scheme is shown, then comparison of the time slot allocation diagram between the conventional HSSR and DVGP schemes and the proposed DHSSBA scheme are shown, then bandwidth allocation principle in the proposed scheme is described where three cases are considered. The proposed data transmission diagram, modified multi-point control protocol

(MPCP) and proposed Gate and Report messages scheduling scheme is presented sequentially and finally jitter and throughput for the proposed DHSSBA scheme are analyzed.

Chapter 4 represents the results and discussion. In this case, computer simulation is used to evaluate the performances of the existing HSSR, DVGP and the proposed DHSSBA schemes. Firstly, average end to end packet delay vs. offered load for the HP data traffic of proposed DHSSBA are compared with the existing HSSR and DVGP schemes. Then maximum packet delay in milliseconds for the HP traffic, average delay in milliseconds for the BE traffic, and average delay in milliseconds for overall traffic, i.e., combined traffic of HP and BE, are compared sequentially. After that absolute delay variation between the DHSSBA and HSSR schemes, and DHSSBA and DVGP schemes, average jitter variation for different offered loads and finally throughput for different offered loads of the DHSSBA are compared with the HSSR and DVGP schemes.

Finally, chapter 5 explains the contribution of the proposed DHSSBA with respect to the performances of the HSSR and DVGP schemes, effect of this proposed scheme on the society, and future works of this scheme.

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CHAPTER II

LITERATURE REVIEW

This chapter presents a comparison between the EPON and GPON. Then, EPON architecture with DBA algorithm, timing diagram and operation of active components are described. The importance of using DBA algorithm over static bandwidth allocation (SBA) algorithm is outlined. Different DBA algorithms come out from different researchers are explained finally.

2.1 Comparison between EPON and GPON

The EPON and GPON both draw heavily from G.983, the BPON standard for their general concepts, i.e., PON operation, ODN framework, wavelength plan, and application. Also, both were designed to better accommodate variable-length IP frames at Gigabit line rates. There are, however, significant differences in the approaches used by each.

2.1.1 Protocol Fundamentals

The EPON is based upon IEEE 802.3 Ethernet that was modified to support point-to-multipoint (P2MP) connectivity. Fig. 2.1 shows the comparison between EPON and GPON. Ethernet traffic is transported natively and all Ethernet features are fully supported. The GPON, on the other hand, is fundamentally a transport protocol, wherein Ethernet services are adapted at the OLT and ONT Ethernet interfaces and carried over an agnostic synchronous framing structure from end to end [1].

2.1.2 Framing/Service Adaptation

The GPON transmission convergence (GTC) layer is responsible for mapping service-specific interfaces (e.g. Ethernet) into a common service-agnostic framework. Ethernet frames are encapsulated into the GTC encapsulation method (GEM) frames, which have a GFP-like format (derived from Generic Frame Procedure ITU G.7401). The GEM frames are, in turn, encapsulated into a SONET/SDH-like GTC frame in both the upstream and downstream directions that is transported synchronously every 125 μs over the PON. In contrast, the EPON carries Ethernet frames natively on the PON with no changes or modifications. There is no need for extra adaptation and encapsulation [1].

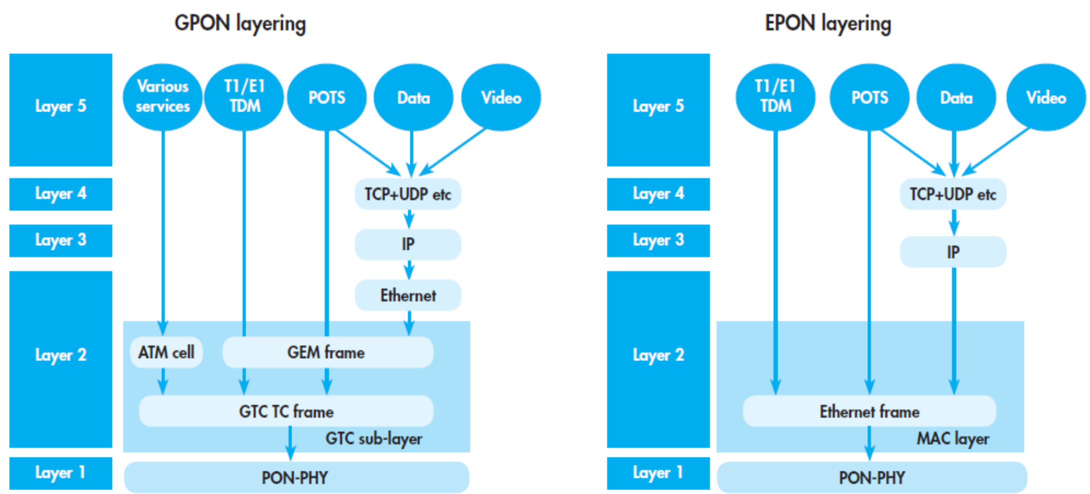

Fig. 2.1 GPON vs. EPON protocol [1].

2.1.3 Service Hierarchy

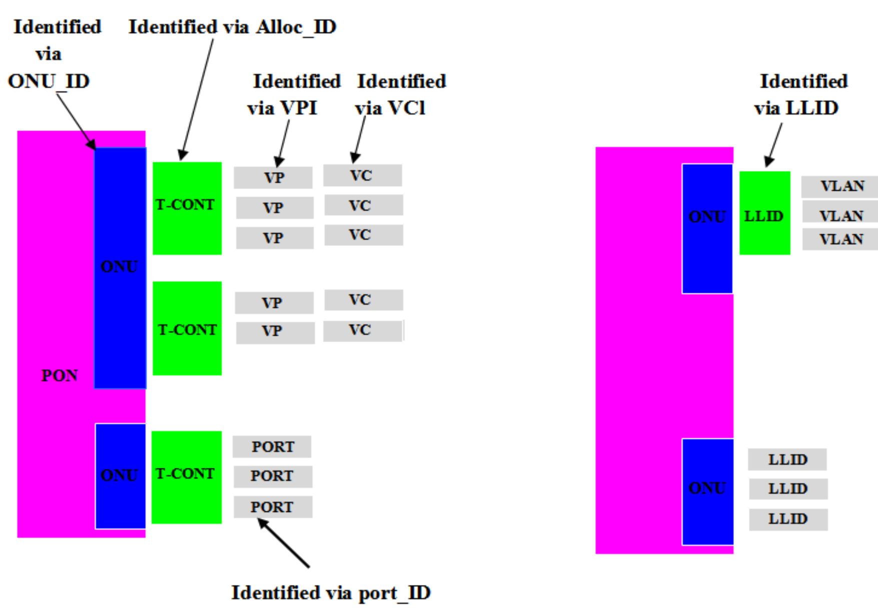

Fig. 2.2 Service hierarchy [1].

Since the operation of PON is P2MP in nature, the OLT must be able to uniquely identify and communicate with each ONT. EPON uses a LLID to uniquely address an ONT. In addition, VLAN_IDs are used for further addressing in order to deliver VLAN-based services. In the downstream direction, the OLT attaches the LLID to the preamble of the frame to identify the destination ONT [1]. Fig. 2.2 shows the service hierarchy.

In GPON, one or more traffic containers (T-CONT) are created between the OLT and an ONT. This T-CONT allows for the emulation of a point-to-point virtual connection between the OLT and ONT and the subsequent TDM of the downstream bandwidth between T-CONTs. Within each T-CONT there can exist multiple port IDs to identify individual ONT ports within a single ONT.

2.1.4 DBA Algorithms

Optionally, both the GPON and EPON support DBA algorithm. This is used for real-time variation of timeslot allocation to ONTs, which increases throughput as a function of upstream demand [1]. DBA elements in GPON and EPON are summarized in Table 2.1.

Table 2.1 DBA elements in GPON and EPON [1].

	GPON DBA	EPON DBA
Granting Unit	GTC overhead	MPCP GATE frame
Control Unit	T-CONT	LLID
Identification of control unit	Alloc-ID	LLID
Reporting mechanism	Embedded OAM	Separate REPORT Frame
Negotiate Procedure	GPON OMCI	N/A

2.1.5 Bandwidth Allocation

The use of TDMA in the upstream direction requires the OLT to schedule each ONT's transmission to avoid collisions. Fundamentally, each ONT receives a grant telling it when to begin and end transmission. In GPON, grants are scheduled per T-CONT; in EPON, per LLID. In the case of GPON, grants are carried in the downstream frame header. A map field within the header specifies the specific T-CONT, start and end {Alloc-ID+Start+End} for each granted upstream window (timeslot). Bandwidth allocation in EPON and GPON are summarized in Table 2.2.

Table 2.2 Bandwidth allocation in EPON and GPON [2].

	EPON		GPON	
Line rate	Downstream	1.25 Gbps	Downstream	1.24416/ 2.48832Gbps
	Upstream	1.25 Gbps	Upstream	1.24416 Gbps
	Bit rate after 8B/10B line coding	1 Gbps	Bit rate after scrambling line coding	1.24416 Gbps
Guard time	Laser on-off	512 ns	Laser on-off	25.7 ns
	Automatic gain control (AGC)	96 ns, 192 ns, 288 ns, and 400 ns	Preamble and delimiter	70.7 ns
	Clock and data recovery (CDR)	96 ns, 192 ns, 288 ns, and 400 ns		
Frame size	Ethernet frame	64–1518 bytes	General encapsulation method (GEM) - GEM header	5 bytes
			General encapsulation method (GEM)- Frame fragment	1518 bytes
Overhead for bandwidth allocation	GATE/REPORT	64 bytes (smallest size of Ethernet frame)	Status report message	2 bytes

In EPON, grant messages are sent per LLID, as separate MAC-Control client frames (GATEs), between regular Ethernet frames. Each grant specifies the {LLID+Start+Length}[1-2].

2.1.6 Control Messages

In GPON, there are three different types of control messages: OMCI, OAM, and PLOAM. Their roles are shown in the table 2.3 [1].

Table 2.3 Control message [1].

Control Channel	Format	Used for
OMCI	Ethernet or ATM	Provisioning of ONT service defining layers above the GTC (e.g., via EMS)
Embedded OAM	Header overhead	BW granting, encryption key switching, and DBA
PLOAM	ATM	Auto discovery and all other PMD and GTC management info. PLOAM messages are directed to ONTs or FF for broadcasts.

In contrast, EPON utilizes IEEE 802.3ah OAM messages for provisioning, fault isolation and performance monitoring in conjunction with SNMP sets and gets through IETF MIBs. Additional control messages are MPCP GATEs/REPORTs for bandwidth granting.

2.1.7 ONT Discovery & Activation

Both the EPON and GPON support automatic ONT discovery and activation mechanisms. GPON uses the serial number (SN) for ONT authentication. There are two methods for activating ONTs [1].

- Method A - The SN of the ONT is registered in advance at the OLT by the operator.
- Method B - The SN of the ONT is not registered at the OLT by the operator/EMS.

Method B requires an automatic detection mechanism of the SN. If a new ONT is detected, an ONT-ID is assigned and the ONT is activated.

Traditionally, EPON does not authenticate via the SN, but, instead, uses the ONT MAC Address in order to assign an LLID. However, some vendor-specific EPON implementations optionally utilize the ONT's SN.

2.1.8 Encryption

Both the EPON and GPON support AES-128 bit encryption. For GPON, key management messages are exchanged via PLOAM cells. Upon request by the OLT, the ONT sends a new key three times. Once received, the OLT toggles a bit in the GTC header to initiate a key switch. For EPON, key management messages are either via a management VLAN or via IEEE 802.3ah OAM messages depending on vendor implementation.

2.1.9 Ethernet Service Support

Since EPON is an IEEE Ethernet standard and utilizes Ethernet switches within its silicon, it can natively support all of the 802.1 and 802.3 features of Ethernet, including VLAN tags, prioritization, OAM, etc. All Ethernet services can be natively delivered in a manner identical to what is done with switched Ethernet today.

Since GPON only defines the transport of Ethernet frames, there is no native Ethernet functionality. Ethernet switches must be placed either in front of or within GPON OLTs and ONTs to provide any additional Ethernet capabilities. Capabilities are, thus, unique to each manufacturer's implementation [1].

2.1.10 Bridging

Since the cross-connect at the GPON OLT is not an Ethernet switch, GPON cannot support standard Ethernet bridging. Thus, in order to support standard bridging, there would be the need for an Ethernet switch upstream of the OLT cross-connect, either externally or in an aggregation point in the same chassis [1].

2.1.11 Transparent LAN Services (TLS)

Transparent LAN services (TLS) is achieved via VLAN tunneling on Ethernet switches. Without these in the GPON OLT chassis, one would need to use external Ethernet switches in order to achieve the same result. The GEM cross-connect cannot inspect VLANs in order to make the appropriate forwarding decisions [1].

2.1.12 Reach

With either protocol, the practical limitation to reach comes from the optical-link budget. With the reach of both protocols currently specified at approximately 20 kilometers, the difference in split rates, the number of ONUs supported by one OLT is a point of differentiation. The GPON promises to support up to 128 ONUs. With the EPON standard, there is no limit on the number of ONUs. Depending on the laser diode amplitude, when using low-cost optics, EPON can typically deliver 32 ONUs per OLT, or 64 with forward error correction (FEC) [2].

2.1.13 Per Subscriber Cost

The use of EPON allows carriers to eliminate complex and expensive ATM and SONET elements and to simplify their networks, thereby lowering costs to subscribers. Currently, the EPON equipment costs are approximately 10 percent of the costs of the GPON equipment, and EPON equipment is rapidly becoming cost-competitive with VDSL [2].

2.1.14 Usable Bandwidth

Bandwidth guarantees vary between the two protocols: GPON promises 1.25 Gbps or 2.5 Gbps downstream and upstream bandwidths scalable from 155 Mbps to 2.5 Gbps. The EPON delivers 1 Gbps symmetrical bandwidth. Gigabit Ethernet service of EPON actually constitutes 1 Gbps of bandwidth for data and 250 Mbps of bandwidth for encoding.

The approach of EPON, as part of the Gigabit Ethernet standard, parallels that of Fast Ethernet, which also uses 25 percent for encoding. 1.25 Gbit service of GPON specifies a usable bandwidth of 1.25 Gbps, with no requirement for encoding. But additional 250 Mbps promised by GPON promoters does not stand as a clear advantage for GPON because it may lie not in the sheer bandwidth comparisons, but in the practicality of 1.25 Gbit uplinks.

Gigabit Ethernet interfaces to the aggregation switch, central office, and metro are currently the cost-effective way to aggregate 1 Gbit ports for transport. With no cost-effective switches for 1.25 Gbps available, the added bandwidth promised by GPON, although measurable, could come at a significant premium over the price of EPON equipment. In other words, the low-cost uplink for the foreseeable future is likely to be Gigabit Ethernet, which is the exact bit rate of EPON. In that light, "added" bandwidth of GPON may not prove advantageous for carriers [2].

2.1.15 Efficiency

With both PON protocols, a fixed overhead is added to convey user data in the form of a packet. In EPONs, data transmission occurs in variable-length packets of up to 1518 bytes according to the IEEE 802.3 protocol for Ethernet. In ATM-based PONs, including GPONs, data transmission occurs in fixed-length 53-byte cells (with 48-byte payload and 5-byte overhead) as specified by the ATM protocol. This format makes it inefficient for GPONs to carry traffic formatted according to IP, which calls for data to be segmented into variable-length packets of up to 65,535 bytes.

For GPONs to carry IP traffic, the packets must be broken into the requisite 48-byte segments with a 5-byte header for each. This process is time-consuming and complicated and adds cost to the central-office OLTs as well as the customer premise-based ONUs. Moreover, 5 bytes of bandwidth are wasted for every 48-byte segment, creating an onerous overhead that is commonly referred to as the "ATM cell tax". (This is the case with GPON's ATM encapsulation mode. In its other encapsulation mode, called GEM, the ATM cell tax does not apply).

By contrast, using variable-length packets, Ethernet was made for carrying IP traffic and can significantly reduce the overhead relative to ATM. One study shows that when considering tri mode packet size distribution, Ethernet packet encapsulation overhead was 7.42 percent, while ATM packet encapsulation overhead was 13.22 percent.

In addition, since Ethernet frames contain a vastly higher ratio of data to overhead than GPON, that high utilization can be reached while using low-cost optics. The more precise timing required with GPON results in more expensive optics. High-precision optics are mandatory as part of the GPON standard [2].

2.1.16 Management System

The EPON requires a single management system, versus three management systems for the three layer 2 protocols in GPON, which means EPON results in a significantly lower total cost of ownership. The EPON also does not require multi protocol conversions, and the result is a lower cost of silicon. The GPON does not support multicast services, which makes support for IP video more bandwidth-consuming [2].

2.1.17 Support for CATV Overlay

Both protocols support a cable television (CATV) overlay, which meets requirements for a high-speed downstream video service. The EPON wavelengths are 1490 nanometers downstream and 1310 nanometers upstream, leaving the 1550-nanometer wavelength for a CATV overlay, similar to the wavelengths for BPON and GPON [2].

2.1.18 Network Protection

Both protocols provide vendor-specific and carrier-specific protection. This includes support for vendor-specific and carrier-specific operations, administration and maintenance (OAM) [2].

2.2 Basics of the EPON

Ethernet architecture is based on the concept of connecting multiple computers to a long cable, sometimes called the Ether, thereby forming a bus structure. Each computer is fitted with an Ethernet adapter that includes a unique 48-bit address for that computer. Each computer is joined to the Ether through a transceiver that forms a logical "T". The transceiver receives Ethernet messages on the cable, looks at the address, and either passes the message to its computer, if the address matches, or transmits it down the cable, if the address does not match. [3].

A single (logical) Ethernet cable forms a local area network. Two LANs can be joined through so-called bridges. A bridge is a special computer connected to two LANs. When it receives a message, it determines which of the two networks the computer being addressed is on and forwards the message to the appropriate network. Messages are variable length records that range from 64 to slightly more than fifteen hundred bytes (or "octets") of data. The format of an Ethernet message is called a frame. Internets are formed by joining two or more local area networks, often Ethernets, through routers. When this is done, IP packets of data are enclosed as the data portion of an Ethernet (or other LAN protocol) frame. Ethernet originally operated at 10Mbps [3].

EPON is deployed with bus or tree topology and connects the multiple ONUs with a single OLT which eventually connects to the metro and wide area networks (WANs). A feeder fiber is used to connect the OLT to multiple ONUs and a passive coupler, i.e., splitter/combiner, splits the optical signal into different ONUs in the downstream direction [5-6].

2.2.1 EPON Protocol

To control the P2MP fiber network, EPON uses the MPCP. The MPCP performs bandwidth assignment, bandwidth polling, auto-discovery, and ranging. It is implemented in the MAC Layer, introducing new 64-byte control messages [4, 7]:

− GATE and REPORT messages are used to assign and request bandwidth.

− REGISTER is used to control the auto discovery process.

The MPCP provides hooks for network resource optimization. Ranging is performed to reduce slack, and bandwidth reporting satisfies requirements by ONUs for DBA. Optical parameters are negotiated to optimize performance. The arbitration mechanism mentioned in previous section is called MPCP. The MPCP supports time slot allocation from the OLT to the ONUs. It provides a framework intended to facilitate the implementation of bandwidth allocation algorithms by providing signaling infrastructure for coordinating upstream data transmission. There are two types of modes in MPCP;

- Auto discovery mode and
- Normal mode.

At the beginning of the communication process, an auto discovery mode is used to register newly connected ONUs. This is done without manual intervention so that ONU can join the EPON system without affecting other ONUs. Sometimes, the existing ONUs may lost synchronization with the OLT. Auto discovery will help to resynchronize these ONUs. It employs four MPCP messages which are discovery GATE, REGISTER_REQ, REGISTER and REGISTER_ACK.

Auto discovery works when OLT transmits a discovery GATE message to an ONU. Discovery GATE message is used to discover the slot and length of a new ONU. Discovery GATE message will first be time stamped with the OLT's local time. Once an ONU receives the discovery GATE message, it will set its local time to the timestamp received. Then, ONU sends the REGISTER_REQ message to the OLT. The REGISTER_REQ message contains ONU's source address and timestamp so that the OLT is able to learn the ONU's MAC address and round trip time (RTT). Afterwards, the OLT will send the REGISTER message that contains an LLID. This LLID serves as a unique identification value of ONU. Other than that, it will also send a normal GATE message to that same ONU. ONU will finally send the REGISTER_ACK message as an acknowledgement that the ONU has received the message.

After the new ONUs has been discovered, we need to sustain the communication between the OLT and ONUs. This is the task of the normal mode. Normal mode employs two MPCP messages namely REPORT and GATE messages. A REPORT message is sent by an ONU to the OLT to request for a time slot whereas a GATE message is sent from the OLT to an ONU to grant the time slot.

Each ONU will first send a REPORT message to the OLT. The REPORT message can either be transmitted automatically or on demand at either the start or the end of a window. The OLT will then send a GATE message to the ONU as a reply. Here, the MPCP will timestamp the GATE message with its local time before sending the message. This is to allow the ONU to program its local register and update its local clock as per timestamp extracted from the received GATE message upon receiving it. This is important in order for ONU to maintain synchronization with the OLT. The ONU will start to transmit frames for up to the window size at the granted start time [4, 7]. Fig. 2.3 shows the timing diagram of GATE and REPORT messages.

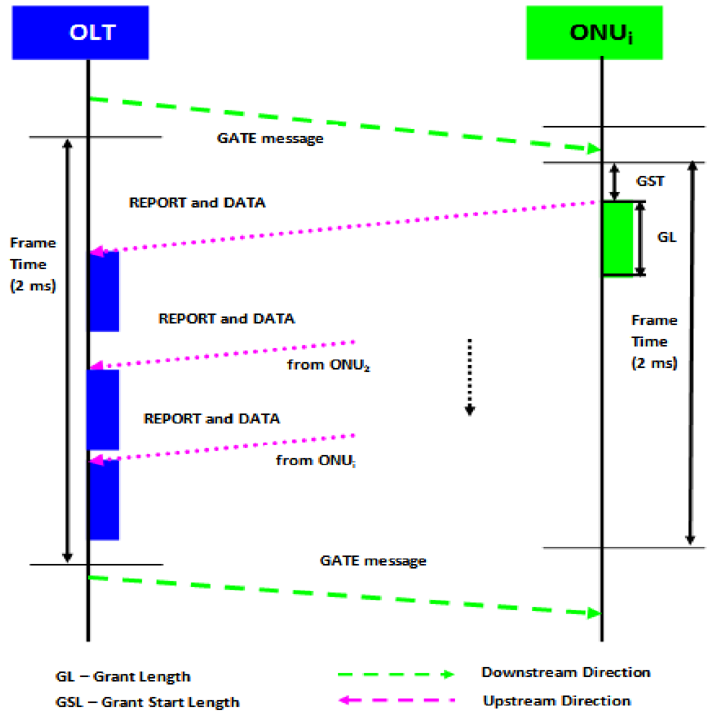

Fig. 2.3 Timing diagram of GATE & REPORT messages.

We assume that the OLT and ONUs are already synchronized through a ranging procedure. Synchronization is making data consistent with data that is distributed in various devices. The ONU*i* detects its grant information from the GATE message through a downlink. As the grant information, the ONU$_i$ transmits its REPORT message and data packets without collisions through an uplink channel. The OLT collects report information from all ONUs and then performs a dynamic bandwidth allocation algorithm considering the reports. The results are broadcasted for the ONUs through a GATE message. The request information with the REPORT message sent in frame $_i$ is actually reflected in the uplink access in frame $_{i+2}$ [8].

2.2.2 ONU and OLT Operation

The ONU performs an auto-discovery process which includes ranging and the assignment of both LLIDs and bandwidth. Using timestamps on the downstream GATE MAC control message, the ONU synchronizes to the OLT timing. It receives the GATE message and transmits within the permitted time period. Fig. 2.4 shows the queue management tasks carried out by each ONU. Here, the ONU maintains three separate priority queues that share the same buffering space.

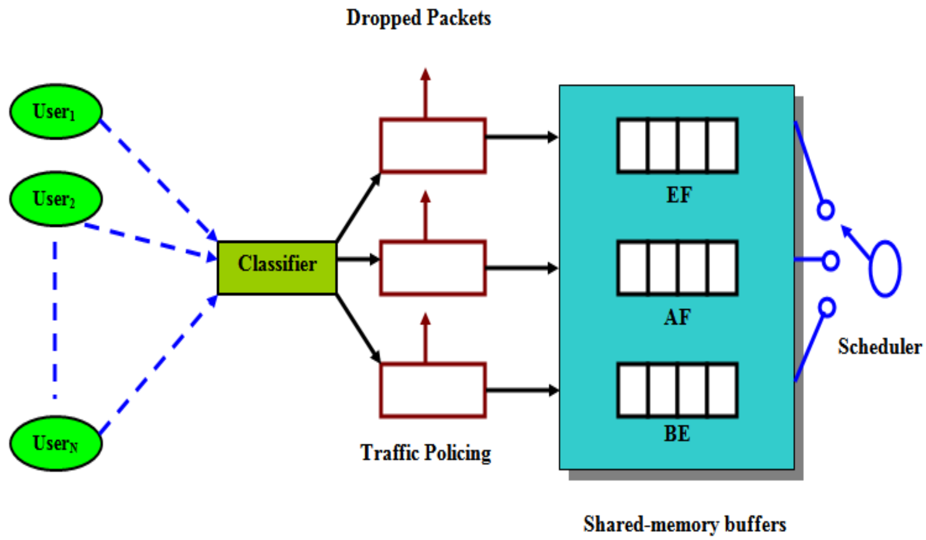

Fig. 2.4 Intra-ONU scheduling [9].

Packets are first segregated and classified (packet classification is done by checking the type-of-service (TOS) field of each IP packet encapsulated in the Ethernet frame) and then placed into their appropriate priority queues. The queuing discipline is as follows: if an arriving packet with higher priority finds the buffer full, then it can displace a lower priority packet. Alternatively, if a low-priority packet arrives and the buffer is full, then the packet is dropped. However, unless some kind of traffic policing is implemented at the ONU to regulate the flow of higher priority traffic and ensure that it conforms to its service level agreement (SLA), lower priority traffic may experience excessive delays and increased packet loss, resulting in a complete resource starvation.

Thus, traffic policing is required at the ONU to control the amount of traffic each user is allowed to send. After classifying the packets, they are checked for their conformance with the service level agreement and unnecessary traffic is dropped. The lower priority traffic is more likely to be dropped in favor of the higher priority traffic; however, control mechanisms are also necessary to control the flow of high-priority traffic if they exceed their agreed service contract [7, 9].

The OLT generates time stamped messages to be used as global time reference. It generates discovery windows for new ONUs, and controls the registration process. The OLT also assigns bandwidth and performs ranging operations. OLTs supporting functions include (1) downstream traffic transmission, (2) bandwidth allocation for upstream traffic for each ONU, and (3) relay upstream traffic to metro or backbone networks. Fiber splitter functions to split optical signal into *N* portions, each transmitted to ONU. Each ONU functions to receive optical signals broadcast from the OLT and accept the frames that destine to it and reject all the frames that do not destine it. Each ONU periodically reports its buffer occupancy status to the OLT and requests slot allocation. Upon receiving the message, the OLT passes this information to the DBA module shown in Fig. 2.5.

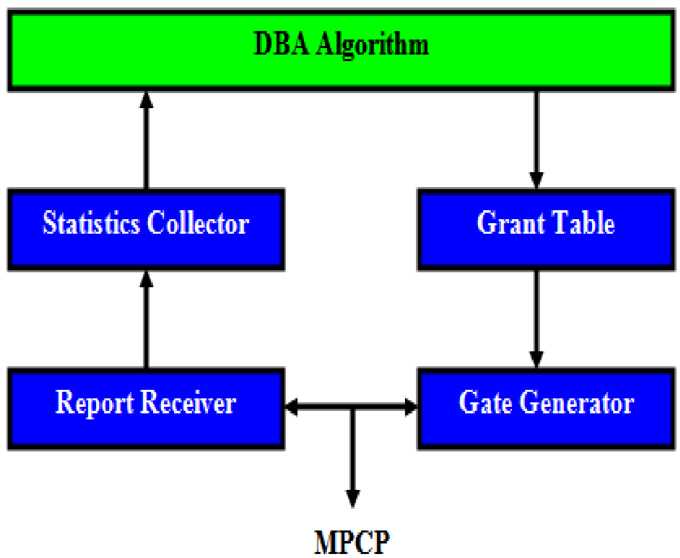

Fig. 2.5 Management block at the OLT [9].

The DBA module in turn performs the bandwidth allocation computation and generates grant messages (note that grant messages are carried by MPCP GATE messages; each GATE might carry more than one grant message). Once the grant table is generated, the OLT transmits to the ONUs this information through the MPCP GATE messages. The grant allocation table is updated by the output of the DBA algorithm. Grant instructions are then compiled into MPCP GATE messages, and transmitted to the ONUs after performing RTT compensation [3, 7, 9].

2.2.3 End-to-End Packet Delay

Different types [13] of delay a packet may experience from the time of its arrival until the time of its transmission in a centralized polling scheme:

- Reporting Delay
- Grant Delay
- Queuing Delay

- Reporting Delay

Buffered data may not be immediately reported upon entering an ONU. Instead, the report message has to be sent during the ONU's next transmission window when it is polled. This imposes a packet delay dependent upon the cycle duration. It can either be zero, if the packet arrives right before sending a report, or it can be the whole cycle duration if the packet had just missed the report. The average reporting delay is therefore half the cycle duration.

- Grant Delay

After the report is sent, the ONU has to wait for a grant to start transmitting. This delay cannot be less than the RTT, which makes it dependent on the OLT– ONU distance. Therefore, the longer this distance is, the more significant the grant delays are.

- Queuing Delay

When an ONU finally receives a grant message, it starts transmitting packets one after another within its granted transmission window. Packets therefore experience queuing delays proportional to the window size. It is worth emphasizing that these three types of delay are pre-transmission delays, delays that occur prior to transmission. Once packet transmission starts, two more delays are introduced, a transmission delay, depending on both the packet length and the upstream transmission rate, and propagation delay, depending on the distance between the ONU and the OLT. Pre-transmission delays depend on the DBA algorithm used, whereas the other delays depend on the network reach, rate, and packet lengths regardless of the DBA algorithm and are therefore irreducible. Thus, the main objective is always to reduce the pre-transmission delays.

It can be seen that grant delays in fact contain both transmission and propagation delays. This makes the retransmission delays of centralized DBA also sensitive to and affected by extending the reach of the network. The increased propagation delay leads to increasing the DBA response time, which causes the average delay to increase.

2.3 Importance of DBA algorithm

The Static Bandwidth Allocation (SBA) algorithm is simple to implement [10]. With SBA algorithm, once bandwidth is assigned to an ONU, it will be unavailable to other ONUs in EPON. Due to the bursty nature of network traffic, it may result in a situation where several time slots overflow even under very light load, causing packet delay for several time slots, while other time slots are not fully utilized even under very heavy traffic. For this reason, the SBA is not preferred.

To increase bandwidth utilization, it is desirable that the OLT dynamically allocates a variable time slot to each ONU based on the instantaneous bandwidth demand of the ONUs. The DBA algorithm is suitable because the IP traffic is burst traffic. With DBA algorithm, when a particular ONU is not using its allocated bandwidth, that bandwidth can be reassigned to another ONU. This feature enables the flexibility of DBA algorithm to meet the different type of traffics in EPON. Without DBA algorithm, the unused bandwidth would be stranded and unusable by other ONUs on the network.

2.4 DBA Algorithms in EPON

One of the main problems of the EPON is to share a common upstream channel by the multiple ONU. For better and efficient upstream data transmission, different DBA algorithms have been proposed by several researchers. The overall performance of the EPON depends on the effectiveness of a DBA algorithm.

The interleaved polling with adaptive cycle time (IPACT) is a very basic and popular DBA algorithm which polls every ONUs in a round robin fashion [11-12]. The IPACT works on a data transmission algorithm called MPCP that uses two control messages, i.e., GATE messages from the OLT to the ONUs and REPORT messages from the ONUs to the OLT, to allocate bandwidth to each ONU for sending data packets in the upstream direction. In the

IPACT, the OLT maintains a polling table to store the relevant information, e.g., number of bytes waiting in each ONUs' buffers, the RTT between the OLT and ONUs. In each time cycle, the OLT transmits the GATE messages to all the ONU to inform about the allocated transmission windows in the next time cycle. However, the IPACT is a very basic DBA algorithm that is not effective for the real time or HP data traffic as it does not provide any priority scheduling technique.

There exist several different services disciplines, i.e., ways for the OLT to determine the granted window size *Wi* (bits) for ONU *i*, depending on the requested window *Vi* (bits). The cycle times and the packet delay for the following three disciplines are as follows:

• **Fixed service**: This service discipline ignores the window, requested by the ONU; instead, the OLT will always grant the maximum window to all the ONU. This causes the cycle time to be constant and maximal: $W_I = W_{\mathrm{MAX}}$.

• **Gated service**: This approach imposes no limit on the size of the granted transmission window; the ONU is always authorized to send the amount of bytes it requested. This means that the cycle time will grow with the traffic load: $W_I = V_I$.

• **Limited service**: With this service discipline, an ONU is granted its requested transmission window, but not more than W_{MAX}. With this approach, the cycle time is variable, but it will not surpass a certain limit: $W_I = \min(V_I, W_{MAX})$.

S. Ramya, et al. [14] have proposed an DBA algorithm where ONU estimates its bandwidth requirement for the current cycle which is the queue length of the data to be transmitted along with the predictive value of the arriving data in the waiting time. Total bandwidth requested by the ONU for servicing all its requests for the current cycle is calculated and the ONU informs the OLT of its requirement by framing the REPORT message with the details and sends it to OLT.

OLT on receiving the REPORT message from an ONU, processes the message and calculates the ONU's bandwidth requirement. The OLT then based on the bandwidth allocation algorithm it follows, grants certain bandwidth to the ONU. In the proposed algorithm, the OLT on receiving a request from the ONU assigns the bandwidth in two levels. In the first level, the OLT grants either its SLA bandwidth or its requested bandwidth based on whether the request is higher or lower than the SLA value. The OLT grants the above bandwidth immediately to the ONU without waiting for request messages from rest of the active ONUs. For ONUs with request higher than its SLA agreement, the first round of GATE message with SLA bandwidth allocation does not generate a REPORT message in response by resetting the 'Force Report' flag in the GATE message.

Whereas, for ONUs with request lower than or equal to its SLA, a single GATE message is sent and the allocation meets its request. This GATE message generates a REPORT message in response to continue with the transmission process for the next cycle. In order to dynamically assign more bandwidth to the requesting ONUs, the OLT does the second level of bandwidth allocation if available. During the second level of allocation, the OLT sends another GATE message to all the high bandwidth requesting ONUs with its excess request of bandwidth if available. This allocation is done in a round-robin fashion starting from the last ONU to the first in the high requesting ONUs list and also high priority requirements of the ONUs are served before any of the low priority requirements are processed.

Thus all high bandwidth request ONUs are given an opportunity to grab more bandwidth if available. The last served ONU is remembered and in the next cycle the round-robin process starts from the previous ONU. The second GATE message unlike the first informs the ONU to respond back with a REPORT message to continue with the transmission process for the next cycle. A GATE message with zero bandwidth is sent to each high requesting ONU if no bandwidth is left for the second level, since a REPORT message has to be generated from these ONU in order to continue with the transmission process for the next cycle and the first round of GATE messages wouldn't have generated REPORT messages.

S. Suganya and S. Palaniammal have proposed [15] a dynamic bandwidth provisioning algorithm that allocates bandwidth efficiently based on traffic statistics measured by traffic monitor. Bandwidth allocation is performed by access routers periodically and is enforced using traffic conditioners as well as the utilization of previous transmission. They signify the interval between two consecutive allocations performed by the algorithm as the revise interval, whose duration is *Tu* seconds. In addition, core routers monitor the flow of the traffic and if congestion detected on some links, it immediately notify to access routers. The access routers solve this situation by implementing dynamic bandwidth allocation. Initially bandwidth is allocated to all active connections by considering their subscribed rate and traffic requirements that are expected based on information collected by access routers. The DBA algorithm is performs in two steps. In the first step, lingering bandwidth by idle and active connections is estimated on each link by implementing the method. In step two, such available extra-bandwidth is allocated with guarantee during the current update interval exclusively to connections that can take advantage of it since they are already fully exploiting their subscribed rate.

Hossen et al. [16] have proposed a new DBA algorithm called adaptive limited DBA (ALDBA) for hybrid PON system where different ONUs are connected to the two different service providers, i.e., fiber to the home (FTTH) and wireless sensor network (WSN). In the ALDBA scheme, two different maximum upstream transmission windows have been considered for the two different service providers as the packet lengths and data rates of the FTTH and WSN are not similar. The ALDBA scheme can effectively mitigate the problem of different data rate and packet lengths of two different service providers but it does not consider the priority based services. For this reason, the ALDBA scheme is also not suitable for the real time applications.

In [17], F. An et al. proposed a new DBA algorithm, i.e., hybrid slot-size/rate **(HSSR)**, where a time cycle is divided into two parts. The 1^{st} part of the time cycle is used for the HP traffic and in every time cycle a fixed bandwidth is allocated to each ONU's HP data packets. The 2^{nd} part of the time cycle is dynamically allocated for the BE traffic of all ONUs in the network. The HSSR scheme can provide better performance for the HP data traffic than the other conventional DBA algorithms. However, bandwidth of the 1^{st} part of each time cycle will be wasted for the lightly loaded ONUs and that leads lower bandwidth utilization and lower throughput than the conventional DBA algorithms. This bandwidth utilization problem can be solved and overall performance can also be improved by using DBA scheme in the 1^{st} half of the time cycle for the HP traffic.

In [18], T. Berisa, et al. formulated a framework for providing absolute delay variation guarantees (i.e., placing an upper bound for experienced delay variation), and analyzed the components of frame delay variation in PONs and OC-enhanced PONs (OC-PON). These analyses yield a DBA algorithm named delay variation guaranteed polling **(DVGP)** that provides absolute delay variation guarantees in these settings. Furthermore, they have shown the duality between providing delay and delay variation guarantees, derived a lower bound for delay variation guarantees in PONs and OC-PONs, and discussed its implications. According to this scheme, total cycle is divided into two parts, 1^{st} part is for HP traffic and 2^{nd} part is for BE traffic. Both parts itself is dynamic in nature but has its fixed upper and lower limit of bandwidth.

In this thesis, we propose a new DBA algorithm called dynamic hybrid-slot-size bandwidth allocation (DHSSBA) algorithm that is a modified version of the HSSR and DVGP schemes. We have proposed a new MPCP scheduling algorithm also that is incorporated to the DHSSBA scheme to mitigate the synchronization problem in the proposed hybrid slot based algorithms. In the proposed scheme, the 1^{st} part of a time cycle is dynamically allocated to the HP traffic of all ONU in the network. Moreover, if the requested window size of the HP traffic of an ONU is larger than the maximum allocated window size for the HP traffic then it will utilize the additional bandwidth from the 2^{nd} part of the time cycle. The drawback of this proposed scheme is that if the offered load of the HP traffic of an ONU is larger and it occupy additional bandwidth from the 2^{nd} part of the time cycle then the BE traffic will suffer from more delay.

The performance of the proposed scheme is evaluated in term of end-to-end packet delay, absolute delay variation, jitter variation and throughput for both the cases of the HP and BE traffic. From the comparison of the proposed DHSSBA scheme to the existing HSSR and DVGP schemes, it is clear that the packet delay of the HP traffic is greatly reduced in the proposed scheme than the existing schemes. In contrast, the packet delay of the BE traffic in the proposed scheme is slightly higher than the HSSR scheme for the higher offered loads. However, the overall delay, i.e., combined delay of the HP and BE traffic, in the proposed scheme is still lower than both the existing HSSR and DVGP schemes.

2.5 Summary

Although both of the EPON and GPON are of PON technologies but they are different with respect to protocol fundamentals, framing/service adaptation, service hierarchy, DBA , control messages, ONT discovery and activation, encryption, Ethernet service support, bridging, TLS, reach, per subscriber cost, usable bandwidth, efficiency, management system, support for CATV overlay, network protection etc. To increase bandwidth utilization, DBA is preferable than SBA. Different DBA algorithms are investigated to obtain QoS as well as better performance.

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CHAPTER III

DYNAMIC HYBRID-SLOT-SIZE BANDWIDTH ALLOCATION ALGORITHM

The chapter presents the architecture of EPON, time slot allocation diagram of the conventional HSSR and DVGP schemes in addition to the proposed DHSSBA scheme for comparison. Then bandwidth allocation and data transmission principles for a time cycle in the upstream direction, Modified MPCP protocol, GATE and REPORT messages scheduling schemes, and analysis of end-to-end delay, jitter and throughput for the proposed DHSSBA scheme are described sequentially.

3.1 EPON Architecture in the Proposed Scheme

The EPON is a topology based on the IEEE 802.3ah standard that has 8B/10B encoding with 1.25 Gbps nominal or 1Gbps data rate effective for both the upstream and downstream directions. The EPON does not require any active elements between the central office and the end users that only comprises with the passive optical components such as optical fiber, couplers, splices, and splitters. The EPON structure with DHSSBA principle is shown in Fig. 3.1. Here, N is the number of ONUs those are connected to the OLT through an optical combiner/splitter. A cycle time is divided into two equal parts, i.e., part 1 is for the HP data traffic and part 2 is for the BE data traffic. The HP and BE data traffic of each ONU are sent to the OLT by using priority management in the ONU [1-2].

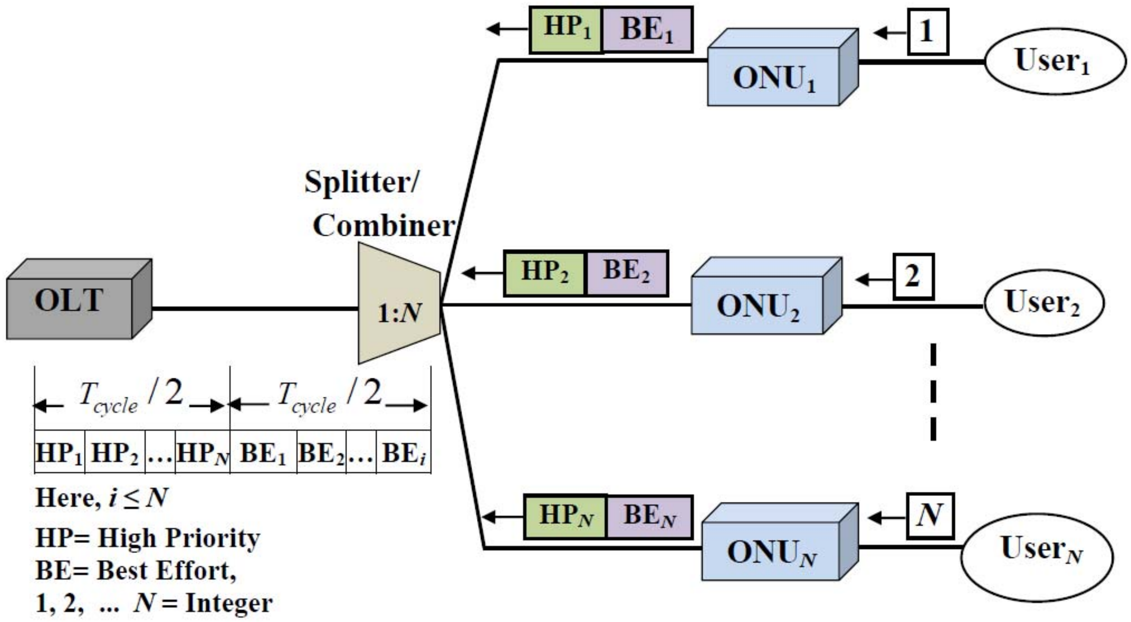

Fig. 3.1 EPON architecture in the proposed scheme.

3.2 Protocol Overview of the Proposed DHSSBA Scheme

Figs. 3.2(a), 3.2(b), 3.2(c) and 3.2(d) show the bandwidth distribution scenarios in different time cycles, i.e., time cycles *j*, *j*+1, and *j*+2, for the conventional, HSSR, DVGP and proposed DHSSBA algorithms, respectively.

The conventional DBA schemes of the EPON are slot-size based, where the OLT grants time slot for all the ONU according to their requested traffic. However, the maximum granted window size of each ONU is upper bounded by the length of a time cycle and number of ONUs in the EPON, i.e., $W(m) = T_{cycle}/N$, where, T_{cycle} is the length of a time cycle and N is the number of ONUs. In these schemes, the HP traffic and the BE traffic are sent within the same time slot in a time cycle as shown in the Fig. 3.2(a) here the bandwidth distribution strategy in the time cycles *j* and *j*+1 are similar.

In the HSSR scheme [2], each time cycle is divided into two parts where the 1st part is steady, i.e., in every time cycle the granted window size for each ONU is fixed. As shown in the Fig. 3.2(b), the 1st part of the time cycle is divided into N time slots and each time slot is allocated for the HP traffic of a particular ONU. The time slot length for the HP traffic of an

ONU at any time cycle, i.e., time cycles j or j+1 or j+2, is fixed. The 2nd part of each time cycle is dynamic and used for the BE traffic of the ONUs. So, depending on the bandwidth requirement of the BE traffic of all the ONU in the network the length of the 2nd part of a time cycle is varied.

In the DVGP [3] scheme, as shown in the Fig. 3.2(c), the HP traffic and the BE traffic are dynamic in nature for the ONUs that means bandwidth of HP and BE for the ONUs can be varied as they require for each of them but maintain the upper and lower limit for the total HP and BE traffic in each time cycle as shown in time cycles j and j+1.

In our proposed DHSSBA scheme, as shown in the Fig. 3.2(d), primarily each time cycle is divided into two equal parts, i.e., $T_{cycle}/2$. However, for giving more priority to the HP traffic if the bandwidth demand by the HP traffic is larger than the maximum window size then the length of the 1st part of the time cycle can be extended. In the Fig. 3.2 (d), it is shown that in the time cycle (j+1), the 1st part of the time cycle is extended to the length of ($T_{cycle}/2 + HP_{extra}$). In contrast, the length of the 1st part of a time cycle will be shortened if the bandwidth demand by the HP traffic is lower. In the Fig. 3.2 (d), it is shown that in the time cycle (j+2), the 1st part of the time cycle is shortened to the length of ($T_{cycle}/2$ - BE_{extra}). That means, in the proposed scheme, the length of a time cycle for the HP traffic is dynamic in nature while in the existing HSSR and DVGP schemes, it is fixed.

The second part of the time cycle is also dynamic and used for the BE traffic for both the proposed and existing schemes. However, one giant slot can be assigned to an ONU's BE traffic if required to reduce the guard intervals. If the network load of the BE traffic is low then the 2nd part of the time cycle is shared by the multiple ONU's BE traffic. The main differences in the bandwidth distribution in the 2nd part of the time cycle for the BE traffic between the proposed and existing schemes is that, in the existing HSSR and DVGP schemes, the maximum length of the 2nd part is fixed, i.e., $T_{cycle}/2$ as shown in the Fig. 3.2 (b) and 3.2(c) while, in the proposed scheme, the length of the 2nd part of the time cycle can be increased or decreased depending on the bandwidth demand of the HP traffic in the network, as shown in time cycle (j+1) and (j+2), respectively, of the Fig. 3.2 (d).

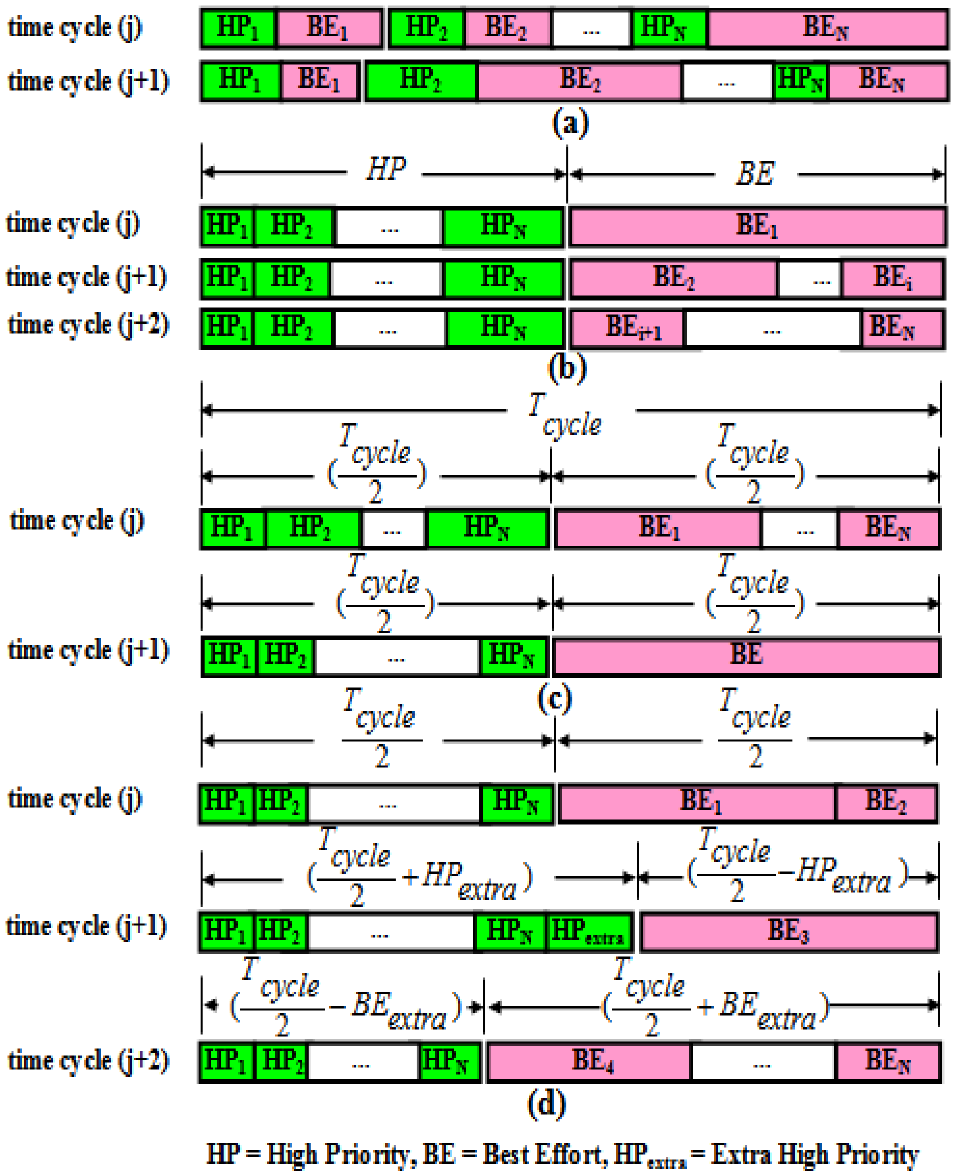

Fig. 3.2 Time slot allocation diagram of (a) Conventional, (b) HSSR, (c) DVGP, and (d) proposed DHSSBA schemes.

3.3 Data Transmission Principle of the Proposed Scheme

Fig. 3.3 shows the data transmission principle for a time cycle in the upstream direction of the proposed DHSSBA scheme. In this figure, the condition is considered that there will be no extra bandwidth demand by the HP traffic of all the ONU, i.e., the summation of the requested window size by the HP traffic of all the ONUs will be fitted into the 1st part of the time cycle. In contrast, the BE traffic of all the ONUs will be fitted into the 2nd part of the time cycle.

From the figure, it is clear that at first the granted window size of the HP traffic of ONUs 1 to N is transmitted to the OLT followed by the bandwidth requests for the next time cycle for both the HP and BE traffic.

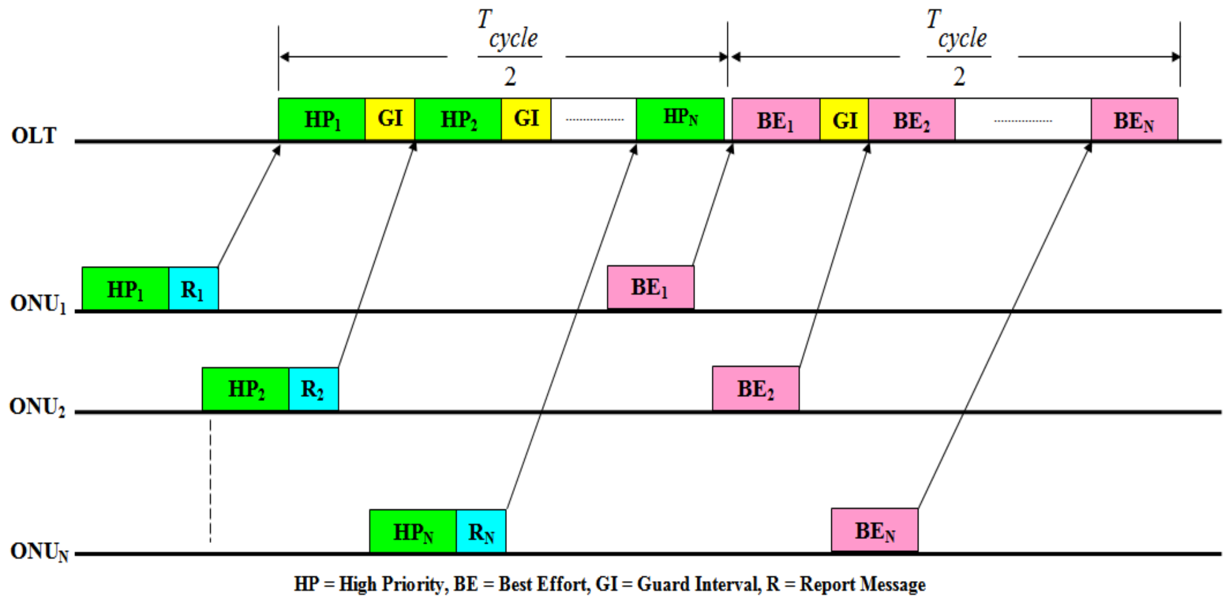

Fig. 3.3 Data transmission diagram in the proposed DHSSBA scheme.

3.4 Bandwidth Allocation Principle in the Proposed Scheme

In the proposed DHSSBA scheme, the maximum transmission windows of an ONU for both the HP and BE traffic are $W(m)_{HP}=T(m)_{cycle}/(2N)$ and $W(m)_{BE}=T(m)_{cycle}/(2N)$, respectively. Here, $W(m)_{HP}$ is the maximum transmission window for the HP traffic, $W(m)_{BE}$ is the maximum transmission window for the BE traffic, $T(m)_{cycle}$ is the maximum length of a time cycle and N is the number of ONUs in the network. According to the proposed scheme, the allocated transmission window of an ONU for both the HP and BE traffic are depended on the following three cases:

Case I:

If the overall bandwidth demands, i.e., for both the HP and BE traffic, of all the ONU are low then the granted transmission windows at a time cycle for both the HP and BE traffic of the ONU i is calculated using equations (3.1) and (3.2):

$$W(G)_{HP(i)} = W(R)_{HP(i)} \quad \text{if } \mathrm{W(R)_{HP(i)}} \leq \mathrm{W(m)_{HP}} \tag{3.1}$$

$$W(G)_{BE(i)} = W(R)_{BE(i)} \quad \text{if } \mathrm{W(R)_{BE(i)}} \leq \mathrm{W(m)_{BE}} \tag{3.2}$$

where, $W(R)_{HP(i)}$ and $W(R)_{BE(i)}$ are the requested window sizes for the HP and BE traffic of ONU *i* at a time cycle, respectively, $W(G)_{HP(i)}$ is the granted window size for the HP traffic and $W(G)_{BE(i)}$ is the granted window size for the BE traffic of ONU *i* at a time cycle.

Case II:

If the network is heavily loaded and the requested window size of the HP traffic is larger than the $W(max)_{HP}$ then the total excess requests of all the ONUs are calculated and this excess bandwidth is granted from the 2nd part of the time cycle. In this case, the allocation of the excess bandwidth from the 2nd part of the time cycle does not depend on the conditions of the BE traffic. That means for any case of the BE traffic, either heavily loaded or lightly loaded, this excess bandwidth is allocated to the HP traffic. This principle is strictly maintained to improve the performance of the real time data traffic in the EPON. Following equation is used to calculate the excess bandwidth for the HP traffic of the heavily loaded ONUs:

$$W(extra)_{HP} = \sum_{i=1}^{n} \left(W(R)_{HP(i)} - W(m)_{HP} \right) \tag{3.3}$$

here, $W(extra)_{HP}$ is the total extra bandwidth for the HP traffic from the 2nd part of the time cycle and *n* is the number of heavily loaded ONUs of the HP traffic.

Finally, this $W(extra)_{HP}$ bandwidth is fairly distributed for the HP traffic among the *k* heavily loaded ONUs of the network. Following formula is used to allocate the transmission window to the HP traffic of the ONUs in the proposed DHSSBA scheme:

$$W(G)_{HP(i)} = \begin{cases} W(R)_{HP(i)} & \text{if } \mathrm{W(R)_{HP(i)}} \leq \mathrm{W(m)_{HP}} \\ W(R)_{HP(i)} + \dfrac{W(extra)_{HP}}{\sum_{k=1}^{n} W(R)_{HP(k)}} * \mathrm{W(R)_{HP(i)}} & \text{if } \mathrm{W(R)_{HP(i)}} > \mathrm{W(m)_{HP}} \end{cases} \tag{3.4}$$

In this case, the granted window for the BE traffic of a heavily loaded ONU can be up to the remaining transmission window, i.e., $\{T(m)_{cycle}/2 - W(extra)_{HP}\}$, if required. Otherwise, this remaining transmission window is shared by the BE traffic of multiple ONUs. Following equation is used to grant the transmission windows to the BE traffic of the heavily loaded ONUs in the proposed scheme:

$$W(G)_{BE} = \begin{cases} W(R)_{BE(i)} & \text{if } \mathrm{W(R)_{BE(i)}} < \left(\dfrac{\mathrm{T(m)_{cycle}}}{2} - \mathrm{W(extra)_{HP}} \right) \\ \dfrac{T(m)_{cycle}}{2} - W(extra)_{HP} & \text{if } \mathrm{W(R)_{BE(i)}} > \left(\dfrac{\mathrm{T(m)_{cycle}}}{2} - \mathrm{W(extra)_{HP}} \right) \end{cases} \tag{3.5}$$

Case III:

In this case, the HP traffic of all the ONUs are considered as lightly loaded and the condition is shown in equation (3.6):

$$\sum_{i=1}^{N} W(R)_{HP(i)} < T_{cycle} / 2 \tag{3.6}$$

While the BE traffic of all the ONU are heavily loaded and the condition is shown in following equation (3.7):

$$\sum_{i=1}^{N} W(R)_{BE(i)} > T_{cycle} / 2 \tag{3.7}$$

As in the equation (3.3), the excess bandwidth $W(extra)_{BE}$ for the BE traffic is calculated using the equation bellow:

$$W(extra)_{BE} = \sum_{i=1}^{N} \left(W(m)_{HP} - W(R)_{HP(i)} \right) \tag{3.8}$$

This excess bandwidth is added to the 2nd part of the time cycle to provide more bandwidth for the BE traffic of the heavily loaded ONUs. Following equation is used to allocate the transmission windows to the heavily loaded ONUs of the BE traffic:

$$W(G)_{BE(i)} = \begin{cases} W(R)_{BE(i)} & \text{if } \mathrm{W(R)_{BE(i)}} \le \left(\dfrac{\mathrm{T_{cycle}}}{2} + \mathrm{W(extra)_{BE}} \right) \\ \dfrac{T_{cycle}}{2} + W(extra)_{BE} & \text{if } \mathrm{W(R)_{BE(i)}} > \left(\dfrac{\mathrm{T_{cycle}}}{2} + \mathrm{W(extra)_{BE}} \right) \end{cases} \tag{3.9}$$

From equation (3.9) it is clear that if the BE traffic of an ONU is hugely loaded then a giant window up to the window size of $\{T_{cycle}/2+W(extra)_{BE}\}$is granted. However, if the requested window of the BE traffic of ONU i is less than that of the $\{T_{cycle}/2 +W(extra)_{BE}\}$ then the remaining transmission window W_{rem}, is calculated as:

$$W_{rem} = \left(\frac{T_{cycle}}{2} + W(extra)_{BE} \right) - W(R)_{BE(i)} \tag{3.10}$$

This remaining window is granted to the BE traffic of the next ONUi+1 as required. The main advantage of this giant window allocation to the BE traffic of an ONU is that it can avoid the bandwidth allocation to the BE traffic of the multiple ONUs at a time cycle that reduces the number of guard time as well as overhead.

3.5 Modified Multi-Point Control Protocol of the Proposed Scheme

The MPCP provides the synchronization of data transmission and efficient channel sharing technique by multiple ONUs in the EPON system. Based on the MPCP protocol the OLT calculates the RTT of each ONU and updates its polling table. Fig. 3.4 shows the modified MPCP operation of the proposed DHSSBA algorithm. In the upstream direction, user’s data are classified into two priority groups and stored in the corresponding buffers, i.e., HP and BE buffers. These two buffers in each ONU perform data transfer on the first-in-first-out (FIFO) principle. The buffer management unit (BMU) performs the priority scheduling scheme in each ONU. According to the proposed DHSSBA scheme, the OLT allocates the bandwidth of the HP traffic for each ONUs dynamically and the remaining window is allocated to the BE traffic of one or multiple ONUs according to the gated service scheme [7]. In the downstream direction, this bandwidth allocation is performed by the OLT using the control message GATE.

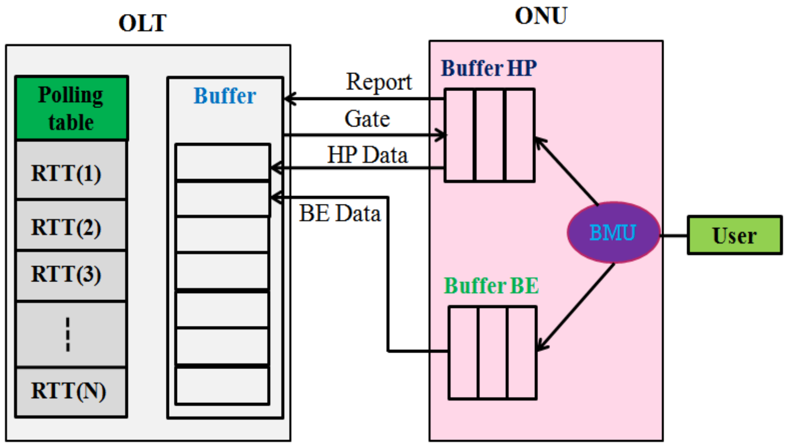

Fig. 3.4 Modified MPCP protocol.

3.6 Proposed GATE and REPORT Messages Scheduling in the DHSSBA Scheme

The MPCP is a supporting mechanism that can facilitate the implementation of various bandwidth allocation algorithms in the PON system. Usually, the MPCP relies on two control messages, i.e., GATE and REPORT messages. The GATE messages are sent from the OLT to the ONUs to inform about the transmission window sizes in the upstream direction of the next time cycle. In contrast, the REPORT messages are sent by all the ONU to inform their queue conditions to the OLT that help to make intelligent bandwidth allocation decisions. Both the GATE and REPORT messages are used in the MAC frames and are processed by the MAC control sub layer [14].

In the DHSSBA scheme, two GATE messages are sent to every ONU in each time cycle. One GATE message is used for assigning bandwidth to the HP data traffic in the first half cycle and other GATE message is used to assign bandwidth to the BE traffic in the second half cycle.

Following points are used to illustrate the proposed MPCP GATE and REPORT messages scheduling algorithm for the DHSSBA scheme.

- From the higher layer, i.e., MAC layer, ONU sends bandwidth request to the OLT using the MPCP REPORT message to transmit two GATE messages, one for the HP data traffic and other for the BE data traffic, to that ONU. Both the GATE messages consist of information about the start of data transmission time and length of the transmission windows of the HP and BE traffic of the ONU. Fig. 3.5 shows the diagram of the MPCP GATE message transmission in the proposed scheme.

- When two GATE messages are transmitted from its higher layer to an ONU, each Gate message consists of the information of time stamps (TSs) with the help of its local clock. Here, in the figure, the TS_1 to TS_N are the TSs of the HP traffic for the ONUs 1 to N, whereas the TS_i to TS_{i+n} are the TSs for the BE traffic of ONUs i to $i+n$.
- Upon receiving the GATE messages from the OLT, the ONU will program its local register with transmission start times and length of transmission windows for both the HP and BE traffic. The ONU also updates its two local clocks with the two received TSs.
- The ONU starts data transmission when its local time matches with the TS.

ONUs sent the REPORT messages automatically to the OLT in each time cycle along with requested window sizes according to the queues of the ONUs. Each ONU generates the REPORT message in the MAC layer and then generates its TS using the local clock. Fig. 3.6 shows the proposed REPORT message scheduling principle in the DHSSBA scheme. In the case of the DHSSBA scheme, two REPORT messages are generated for two types of data traffic, i.e., HP and BE traffic, and after being time stamped they are combined and sent as one REPORT message for a particular ONU. The REPORT message would contain the desire bandwidth in the next time cycle for both the HP and BE traffic. Upon receiving each REPORT message the OLT passes it to the MAC sub layer to make the bandwidth allocation decision based on the ONU's queue size.

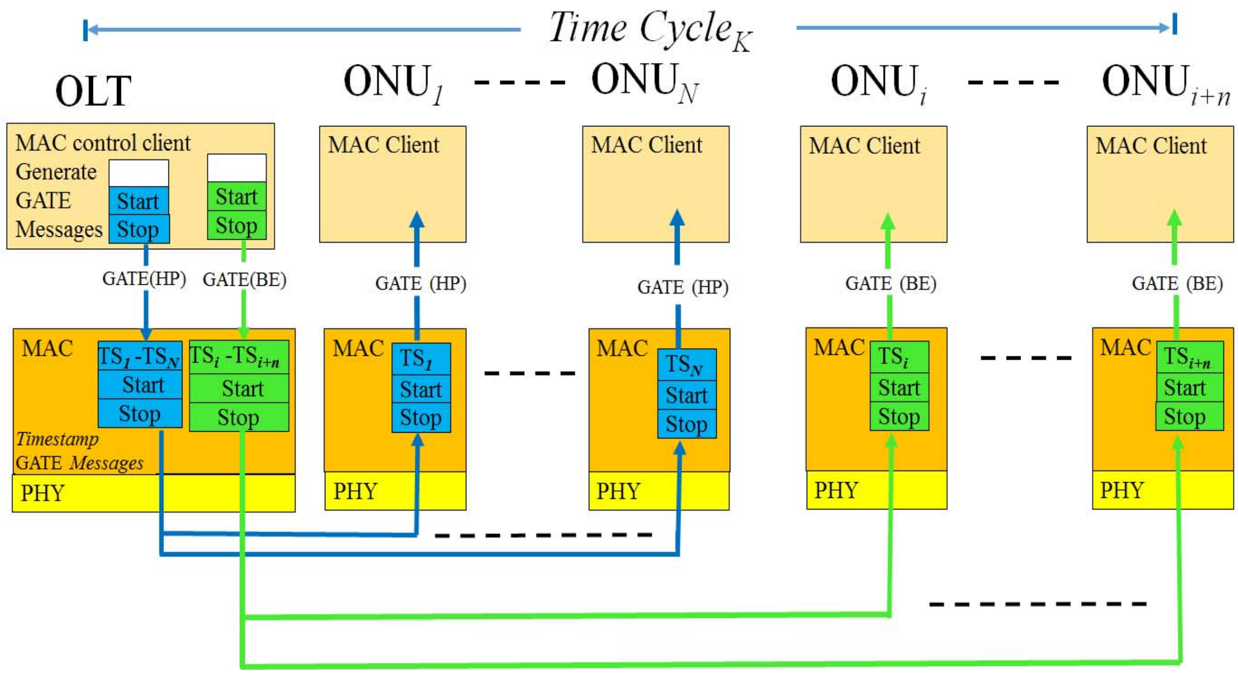

Fig. 3.5 MPCP GATE operation in the DHSSBA scheme.

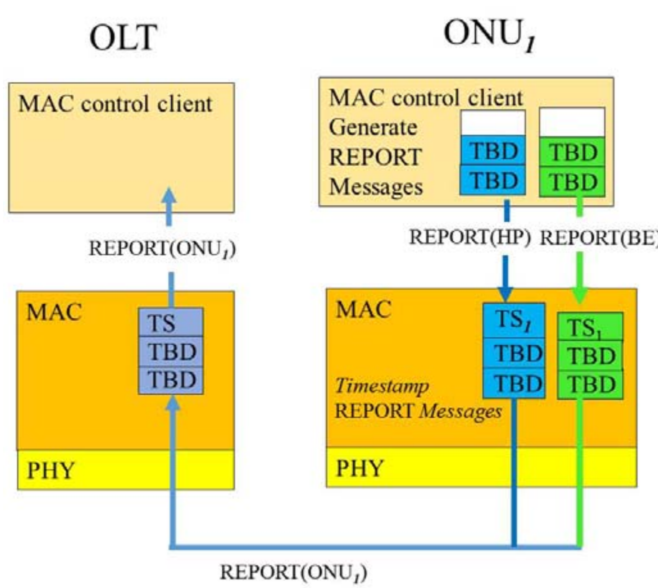

Fig. 3.6 MPCP REPORT message scheduling diagram in the DHSSBA scheme.

3.7 Analysis of End-to-End Delay, Jitter and Throughput for the Proposed DHSSBA Scheme

One of the main objectives of this proposed DBA algorithm is the reduction of end-to-end packet delay for the real time traffic, i.e., HP traffic. Because the bandwidth demands of the HP traffic is increasing day by day. In the proposed scheme, the end-to-end average delay D_{avg} is calculated using the following formulas:

$$D_{avg} = \frac{1}{n}\sum_{j=1}^{n}\left(D_{HP(j)} + D_{BE(j)}\right) \tag{3.11}$$

where, n is the number of time cycle, j is the integer, $D_{HP(j)}$ and $D_{BE(j)}$ are the delay of HP and BE traffic at time cycle j, respectively. The formulas for calculation of D_{HP} and D_{BE} are as follows:

$$D_{HP} = \begin{cases} \sum_{i=1}^{N}\left(W(R)_{HP(i)} + W_{OH}\right) & \text{without congestion} \\ \sum_{i=1}^{N}\left(W(R)_{HP(i)} + W(extra)_{HP(i)} + W_{OH}\right) + T_{cong(i)} & \text{with congestion} \end{cases} \tag{3.12}$$

$$D_{BE} = \begin{cases} \sum_{i=1}^{N}\left(W(R)_{BE(i)} + W_{OH}\right) & \text{without congestion} \\ \sum_{i=1}^{N}\left(W(R)_{BE(i)} + W(extra)_{BE(i)} + W_{OH}\right) + T_{cong(i)} & \text{with congestion} \end{cases} \tag{3.13}$$

where, W_{OH} is the window for overhead which is the summation of guard interval, Ethernet overhead, and REPORT message, and T_{cong} is the congestion delay. The Congestion Time, T_{cong} depends on the network traffic. It can be 0 if the ONUs is lightly loaded. But it can be any value from 0 to the duration of data transmission time in the next time cycle. It depends upon the number of packet in the queues, requested window size, length of the time cycle, retransmission, data collision, etc. Following formula is used to calculate the T_{cong} in our PON system. Here, T_G is the Guard Time.

$$T_{cong(i)} = \sum_{m=i}^{N-i}\left(W(G)_{(m)} + T_G\right) + \sum_{m=1}^{i-1}\left(W(G)_{(m)} + T_G\right) \tag{3.14}$$

Usually, in any DBA algorithm of EPON jitter cannot be avoided. However, jitter is one of the responsible parameters that reduce the quality of real time traffic in EPON. Proposed scheme uses the following analysis to measure the average jitter J_{avg} in the EPON.

$$J_{avg} = \frac{1}{n}\sum_{j=1}^{n}\left|D_{avg(j)} - D_{avg(j+1)}\right| \tag{3.15}$$

where, $D_{avg(j)}$ and $D_{avg(j+1)}$ are the average delay in time cycle j and j+1.

3.8 Summary

In this chapter, the EPON architecture, overview of the proposed DHSSBA scheme, MPCP, bandwidth allocation principle, GATE and REPORT messages transmission diagram with data transmission technique, modified MPCP with proposed GATE and REPORT scheduling scheme, jitter variation, and throughput are discussed.

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CHAPTER IV

RESULTS AND DISCUSSION

In this chapter, we have evaluated the performances the proposed DHSSBA scheme and compared those performances with existing HSSR and DVGP schemes by using computer simulation.

4.1 Performance Evaluation by Simulation

In this section, the performances of the proposed DHSSBA scheme are evaluated in terms of end to end packet delay, jitter, and throughput for both the HP and BE data traffic. The results of the proposed scheme are compared with the existing HSSR and DVGP schemes. Matlab and programming language C++ were used for computer simulation to evaluate the performances of the proposed DHSSBA and existing HSSR and DVGP schemes. In the simulations, we have assumed the PON architecture with one OLT and 16 ONUs in a tree topology based EPON system. The distance between the OLT and ONUs were considered in the range of 10-20 km and 1 Gbps transmission speed for both the upstream and downstream directions. We also have used the packet length of 1500 bytes [1] for the HP traffic while the double packet length was considered for the BE traffic, the conventional BE traffic consists of large amount of data traffic, i.e. bulky data. Example of BE traffic are Email, electronic documents, paper, electronic images etc. Offered load was considered as one to ten packets, here Network traffic load or data traffic is the amount of data moving across a network at a given point of time. For example, the 0.8 traffic loads means eighty percent of the maximum offered load in the network. The simulation parameters are summarized in Table 4.1.

Table 4.1 Simulation parameters.

Symbol	Explanation	Value
N	Number of ONUs	16
T_{cycle}	Length of time cycle	2 ms
D	Distance between the OLT and ONUs	10-20 km
T_G	Guard Time	5 μs
R_U	Transmission speed in both the upstream and downstream directions	1 Gbps
T_E	Length of Ethernet overhead	576 bits
T_R	Length of Report message	304 bits
T_P	Length of a data packet for the HP traffic	1500 bytes
P_{HP}	Maximum number of packets for HP	0 to10

4.2 Comparison of Average End-to-End Packet Delay

Fig. 4.1 shows the comparison of average end-to-end packet delay vs. offered load for the HP data traffic of the proposed DHSSBA with the existing HSSR and DVGP schemes. From the Fig. 4.1, it is clear that the proposed scheme provides almost constant average delay for the HP traffic for any value of the offered load. In contrast, the average packet delay for the HP traffic for the existing HSSR and DVGP schemes increase rapidly after the offered load of 0.4. At the lowest offered load of 0.1 the average packet delay of the HP traffic for the HSSR scheme is 1.5 times larger than the proposed scheme. However, at the highest offered load of 1.0 the average packet delay for the HP traffic in the existing HSSR scheme is 2.5 times and in the DVGP scheme is 2.0 times larger than the proposed scheme. From these results it is clear that the proposed scheme is very efficient to maintain less packet delay even for the heavily loaded ONUs.

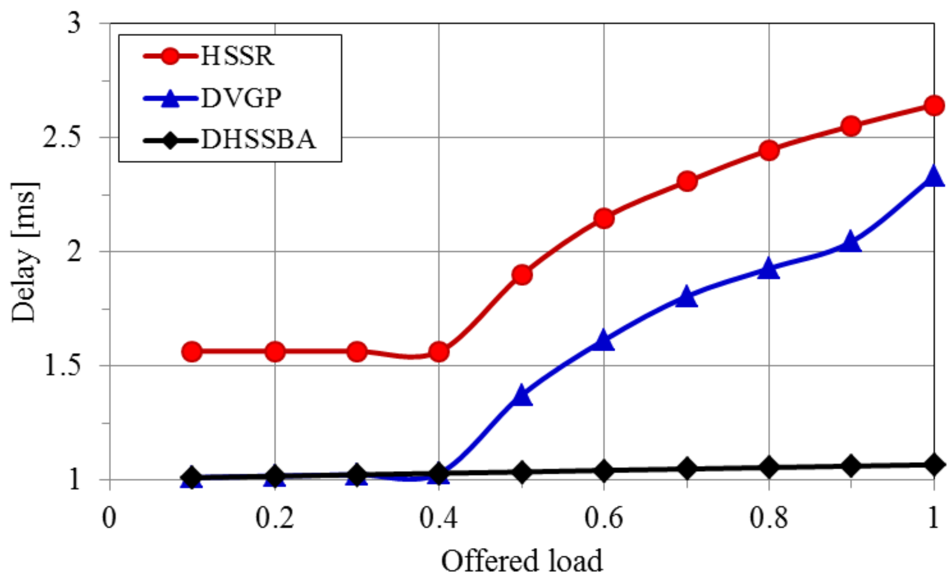

Fig. 4.1 Average delay in milliseconds for the HP traffic.

4.3 Comparison of Maximum Packet Delay

Fig. 4.2 shows the comparison of the maximum delay vs. offered loads of the proposed DHSSBA scheme with the existing HSSR and DVGP schemes. Alike the average delay the proposed scheme also provide constant maximum delay up to the offered load of 1.0 and at this offered load the existing DVGP and HSSR schemes provide about 3.0 and 3.5 times more maximum delay, respectively, than the proposed scheme. Similarly, the proposed scheme provides 100% throughput for the HP traffic without suffering from the congestion problem while in both the existing HSSR and DVGP schemes it is only 40%. So, it can be concluded that the proposed scheme provides better delay performance than the existing schemes for both the cases of average and maximum delays.

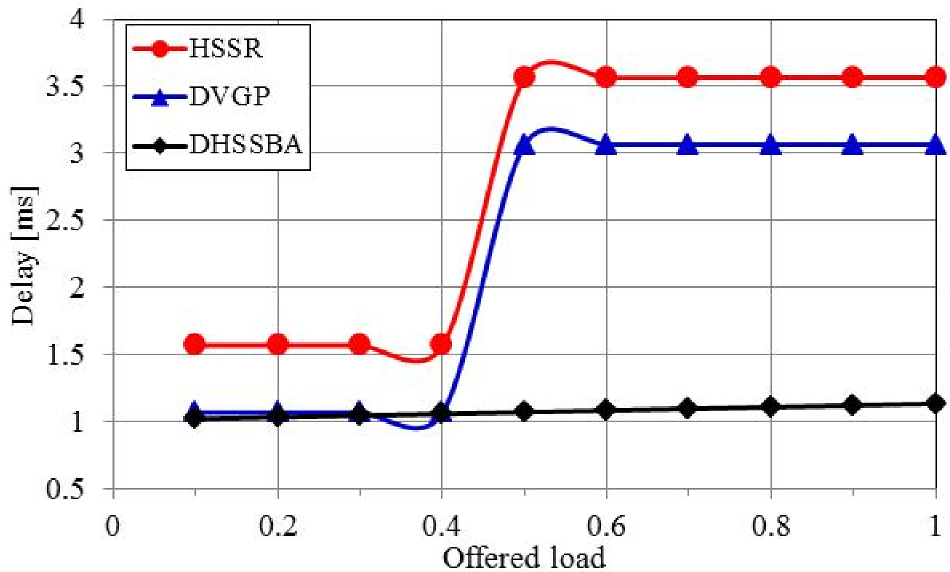

Fig. 4.2 Comparison of maximum packet delay for the HP traffic.

4.4 Comparison of Average Packet Delay for the BE and Combined Data Traffic

Figs. 4.3 and 4.4 show the average end-to-end delay against offered loads for the BE traffic and combined traffic, i.e., combination of the HP and BE traffic, respectively. From the Fig. 4.3 it is found that the proposed scheme provides marginally higher delay than the existing schemes at the offered load of larger than 0.8. So, proposed scheme has some drawbacks in the case of the BE traffic at the offered loads higher than 0.8. However, from the Fig. 4.4 it is clear that the combined average delay for the proposed scheme is lower than the existing HSSR and DVGP schemes for any value of the offered load. Therefore, even the proposed scheme provides larger delay than the existing scheme at higher offered loads for the BE traffic the combined average delay of the network is still lower in the proposed scheme. These results prove that the proposed scheme is more effective than the existing schemes in term of average packet delay for both the HP and combined traffic.

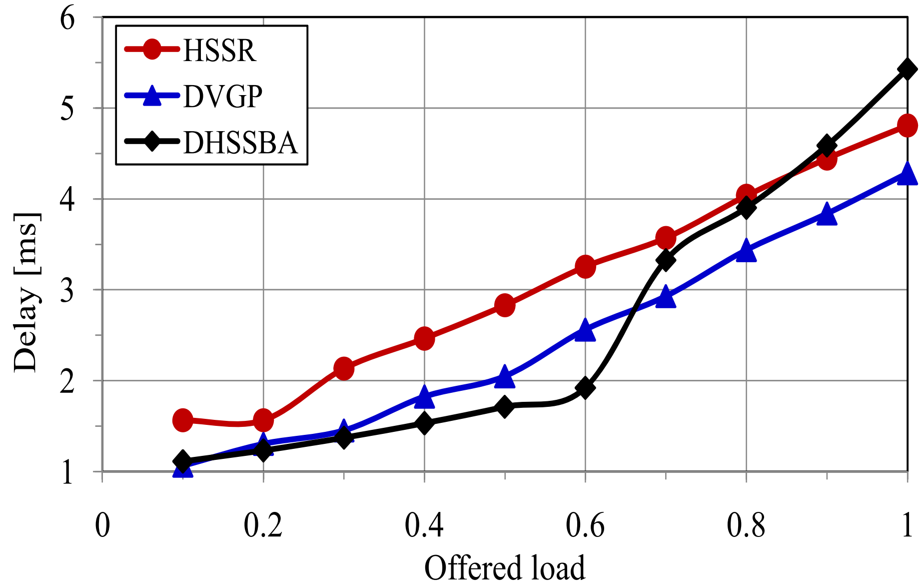

Fig. 4.3 Average delay in milliseconds for the BE traffic.

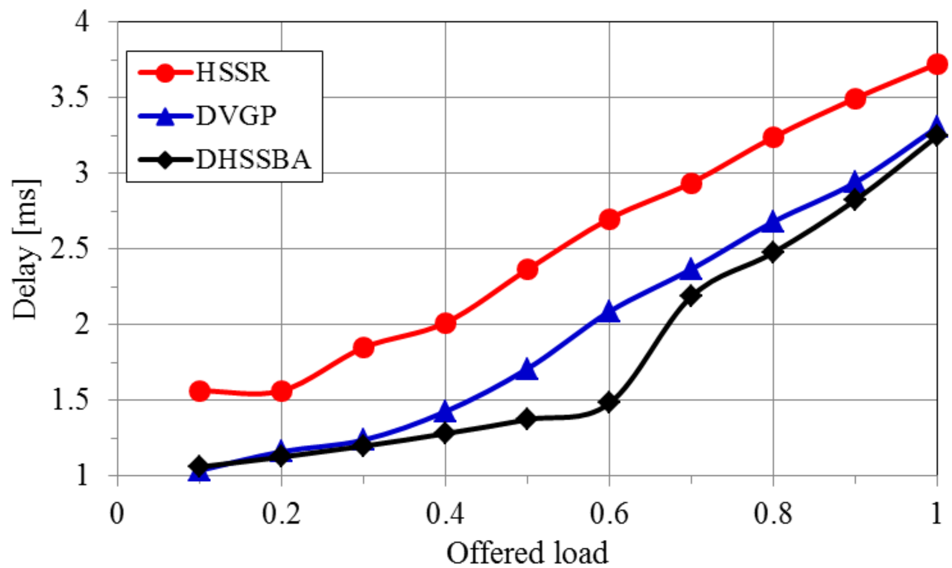

Fig. 4.4 Average delay in milliseconds for the combined traffic of HP and BE.

4.5 Absolute Delay and Jitter Variations

We have evaluated the absolute delay variation and jitter performance of the proposed DHSSBA scheme and compare those with the existing HSSR and DVGP schemes. Fig. 4.5 and Fig. 4.6 show the instantaneous result of absolute delay variation for different time cycles, i.e., time cycles 1 to 500. From the comparative analysis of these figures, it is clear that the proposed scheme is stronger than the existing HSSR and DVGP schemes in terms of absolute delay variations. The maximum absolute delay variation in the proposed scheme is not more than 12.5 ms while the maximum absolute delay variation in the existing two schemes is about 20 ms.

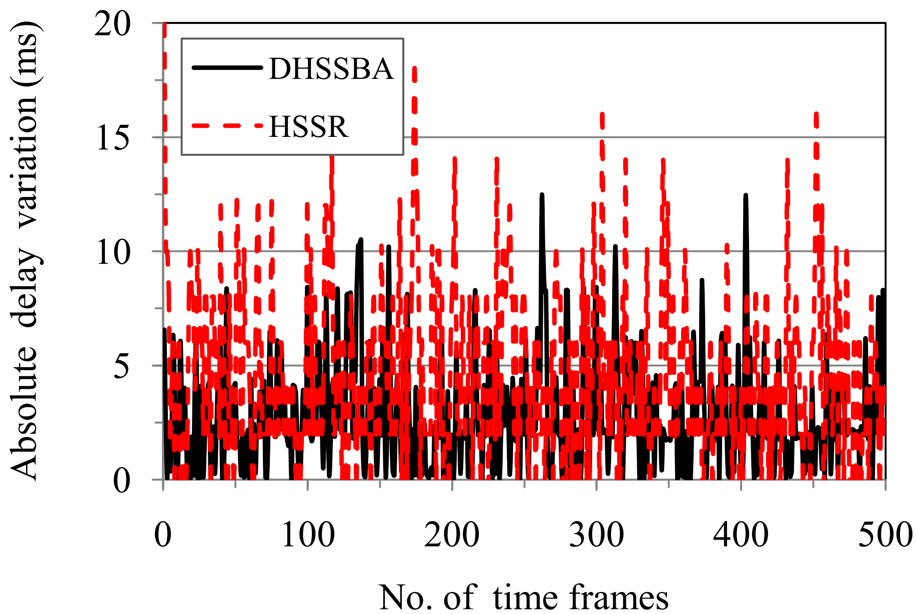

Fig. 4.5 Comparison of absolute delay variation between DHSSBA vs. HSSR.

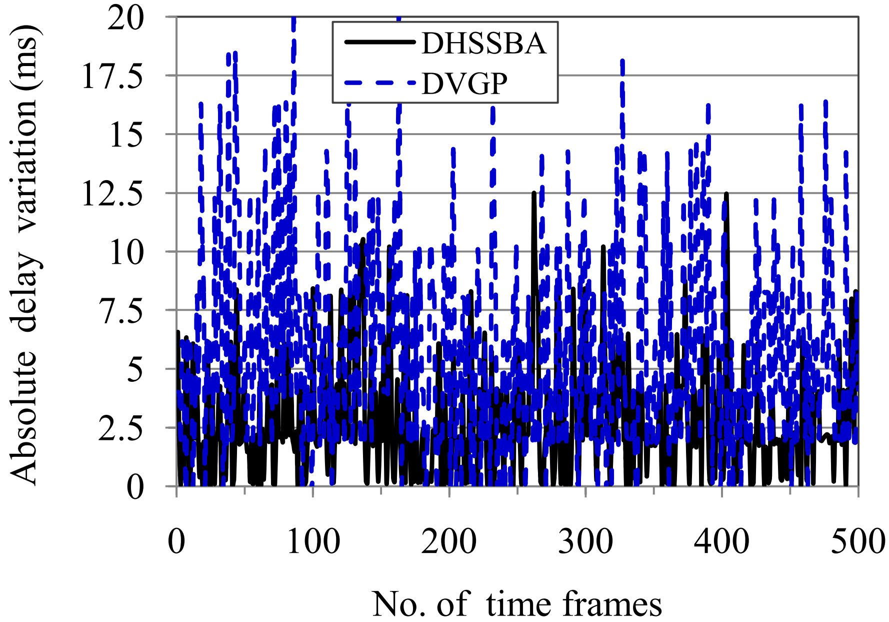

Fig. 4.6 Comparison of absolute delay variation between DHSSBA vs. DVGP.

Fig. 4.7 shows the comparison of average jitter variation vs. offered load for 1.0 ms and 2.0 ms time cycles. This result shows that the proposed scheme can provides almost 0.0 ms average jitter variation up to the offered load of 0.8 for both the cases of 1.0 ms and 2.0 ms cycle times. In contrast, the existing HSSR scheme provide the 0.0 ms average jitter variation only up to the offered load of 0.3 for both the cases of 1.0 and 2.0 ms cycle times. The HSSR scheme suffers from the maximum average jitter variation of 0.17 ms and 0.33 ms at the offered load of 0.4 for both the 1.0 ms and 2.0 ms cycle times, respectively. Also the DVGP scheme provide the 0.0 ms average jitter variation only up to the offered load of 0.3 for both the cases of 1.0 and 2.0 ms cycle times, This DVGP scheme suffers from the maximum average jitter variation of 0.17 ms and 0.34 ms at the offered load of 0.4 for both the 1.0 ms and 2.0 ms cycle times, respectively. On the other hand, the proposed scheme suffers from the maximum average jitter variation of 0.09 ms and 0.19 ms at the offered load of 0.9 for both the 1.0 ms and 2.0 ms cycle times, respectively. The existing HSSR and DVGP schemes suffer from the maximum average jitter variation at the offered load at 0.4 and the offered load of larger than 0.4 the jitter variation is decreased up to the offered load of 0.8. The reason is that the cycle time variation is the largest at the offered load of 0.4 for the considered lengths of time cycles in both the existing schemes.

But the cycle time variation is the lowest at the offered load of 0.8 for the considered lengths of time cycles which provides lowest average jitter variation. Here, the offered load of 0.8 is the optimized value for the considered lengths of time cycle. From this comparative analysis of average jitter variation we can conclude that the proposed scheme provides better jitter performance than the existing scheme for any value of cycle times and offered loads.

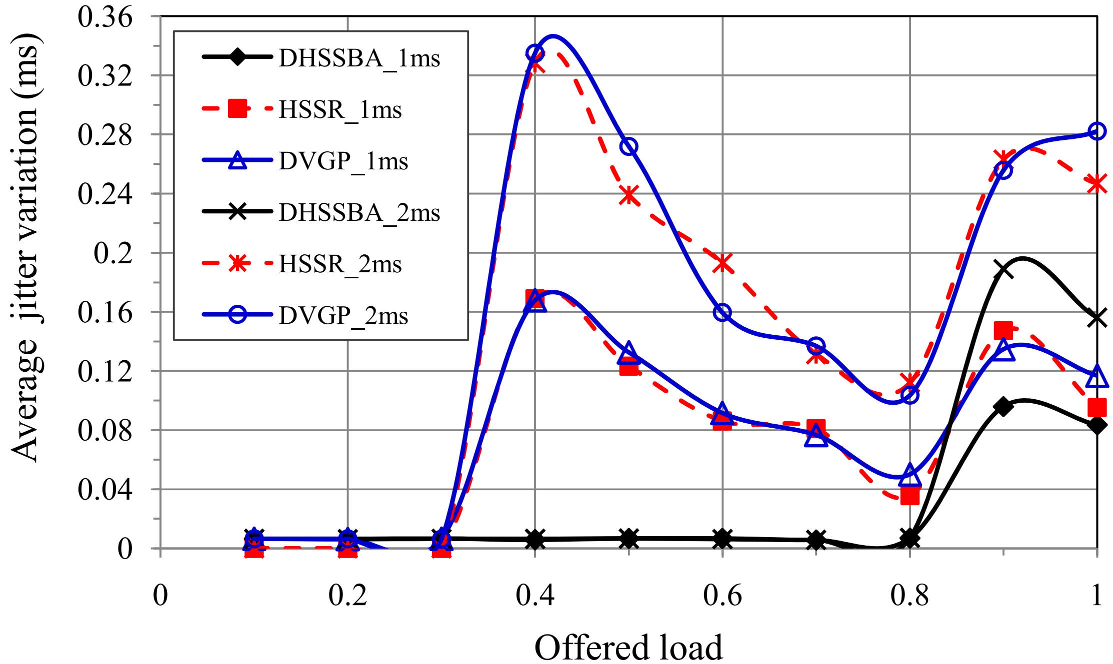

Fig. 4.7 Comparison of average jitter variation for different offered loads.

4.6 Comparison of Throughput

We also have evaluated the throughput of the DHSSBA scheme and compare it with the existing HSSR and DVGP schemes. Fig. 4.8 shows the comparison of throughput for offered loads of 0.1 to 1.0 among the existing and proposed schemes for 2.0 ms cycle time. From the figure, it is easily perceptible that for the HP traffic of the proposed and existing schemes, throughput are similar up to the offered load of 0.6. However, the proposed DHSSBA scheme outperforms the existing schemes in terms of throughput for the offered loads higher than the 0.6 as more bandwidth is allocated for the HP traffic according to our proposed scheme. With the increase of offered loads the throughput difference is also increased and at the maximum offered load of 1.0 it is 95% for the DHSSBA scheme whereas in the case of HSSR and DVGP schemes it is 70%.

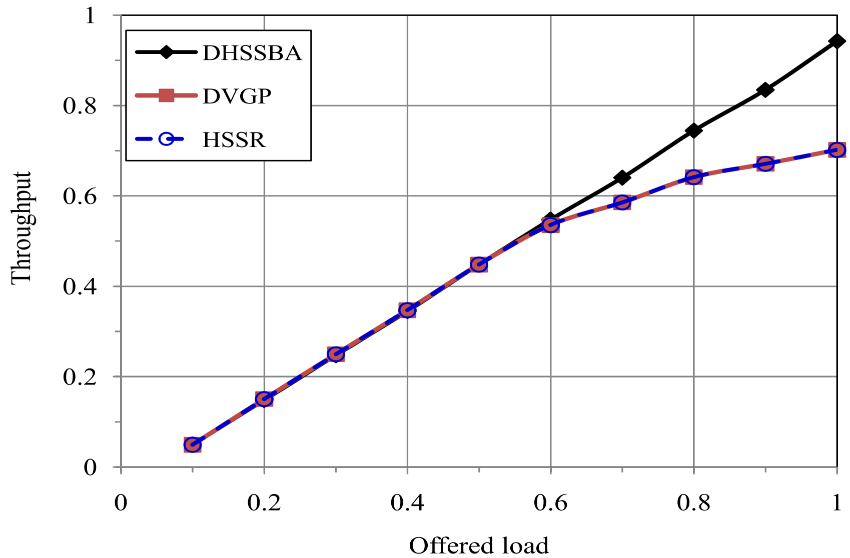

Fig. 4.8 Comparison of throughput for different offered loads.

4.7 Summary

This proposed DHSSBA scheme reduces data congestion problem that reduces the end to end packet delay for the HP traffic with higher throughput and bandwidth utilization. The proposed scheme also reduces the absolute delay variation and jitter problems in the PON system.

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CHAPTER V

CONCLUSION

In this thesis, the aim of the proposed DHSSBA scheme is to focus on the importance of the transmission of HP data traffic without any losses because the end users never want to sacrifice any real time traffic while communicating with others.

5.1 Contributions

In this thesis, we have proposed a new DBA algorithm called DHSSBA scheme which is incorporated with the modified MPCP control messages scheduling scheme. The main objective of this thesis is to improve the performances and QoSs of the HP traffic of PON system. Performances of the proposed scheme are evaluated in terms of the average and maximum packet delay, absolute delay variation, average jitter variation, and throughput. All the simulation results of the proposed DHSSBA and control messages scheduling schemes are also compared to those of the existing HSSR and DVGP schemes. The proposed DHSSBA scheme significantly reduces the average delay than the existing schemes for the HP traffic and also provides constant delay from the very lower value of the offered load to the higher value. At the highest offered load of 1.0 the proposed scheme provides about 60% lower packet delay than the existing schemes for the HP traffic. One of the main contributions of the proposed scheme is that it can significantly reduce the average packet delay for the HP traffic while the overall packet delay is still lower than that of the existing scheme. The simulation results also prove that the proposed scheme provide better results in terms of absolute delay variation, jitter variation and throughput.

5.2 Impact on the Society

End users of telecommunication systems are enjoying modern facilities now a day. Video chatting, online TV, video on demand, online gaming is the popular real time services. Those services require interruption free communication as well as high bandwidth. Now, the whole world is a global village and users of any parts of the world communicating with each other any time like living in a same society and within the same time. Our proposed scheme is based on reducing delay of real time traffic that means high priority traffic. So we think, if it is implemented in the PON technology, users on the internet society will enjoy more bandwidth for real time services in the fiber optic network.

5.3 Future Projection

In our proposed scheme, we have considered the EPON where the distance between the OLT and ONUs is 10 km to 20 km. We have also considered sixteen (16) ONUs and one (01) OLT in a tree topology connection. In the future works, we have interest to do research with more distance between OLT and ONUs, i.e., long reach PON (LR-PON), which may be 100 km or more. We will also try to work with multi-OLT PON system and will more number of ONUs. In this regards, we think QoSs will be improved for the real time services.

LIST OF PUBLICATIONS

International Conference:

[1] **Md. Selim Morshed**, Monir Hossen, Mohammad Mahbbubur Rahman, and Masanori Hanawa, "Dynamic Hybrid Slot Size Bandwidth Allocation Algorithm for Reducing Packet Delay of Real Time Traffic in EPON'', **Best Paper Award,** 1st International Conference on Advanced Information and Communication Technology (ICAICT 2016), Chittagong, Bangladesh, May 16-17, 2016.

International Journal (Accepted):

[1] **Md. Selim Morshed**, Monir Hossen, Mohammad Mahbbubur Rahman, and Masanori Hanawa, "Dynamic Hybrid Slot Size Bandwidth Allocation Algorithm for Reducing Packet Delay of Real Time Traffic in EPON,'' accepted in the **JURNAL TEKNOLOGI.** (http://www.jurnalteknologi.utm.my/index.php/jurnalteknologi/)