Efficient DBA Algorithms for Delay Reduction and Solving the Over-granting Problem of Long Reach PON

By

Shuvashis Saha

A thesis submitted in partial fulfillment of the requirements for the degree of

M.Sc. Engineering

in the Department of Electronics and Communication Engineering

Department of Electronics and Communication Engineering

Khulna University of Engineering & Technology

Khulna 9203, Bangladesh

December, 2017

Declaration

This is to certify that the thesis work entitled "*Efficient DBA Algorithms for Delay Reduction and Solving the Over-granting Problem of Long Reach PON* " has been carried out by *Shuvashis Saha* in the Department of Electronics and Communication Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh. I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for the award of any degree or diploma. Except where states otherwise by reference or acknowledgment, the work presented is entirely my own.

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Acknowledgement

First of all, I wish to thank my Almighty creator, the sustainer who has been showering his endless blessings on us throughout of our life. I would like to thank my honorable thesis supervisor Dr. Monir Hossen, Associate Professor, Department of Electronics and Communication Engineering (ECE), Khulna University of Engineering & Technology (KUET) for accepting me as his student and giving me the directions to finish this thesis. I am grateful to him for his kind inspiration and supports throughout the entire time.

I wish to thank the course teachers of my M. Sc. Engineering degree – Prof. Dr. Md. Mostafizur Rahman, Prof. Dr. Md. Faruque Hossain, Prof. Dr. A.B.M. Aowlad Hossain, and Dr. Sheikh Md. Rabiul Islam, with Course Co-coordinator Prof. Dr. Md. Foisal Hossain, Dept. of ECE, KUET and all of the board of examiners for their time to review the thesis and attend in my defense.

I wish to express my sincere thanks to my family members, my colleagues of KUET, and officers and staffs of KUET. This accomplishment would not have been possible without all of your supports.

Author

Abstract

The conventional open access optical network (OAN) with point to multipoint structure needs active components to cover large number of users in a wide area. Requirement of more active components significantly increase the network deployment costs. Cover large range congregation of point to multipoint networks is one of the effective solutions to reduce the network deployment costs. This idea offers the long-reach passive optical network (LR-PON) concept with 100 Km spanning the conventional OAN without any active components between sources to destination. However, the LR-PON involves larger propagation delay as well as end-to-end packet delay compared to the conventional PON system, i.e., spanning distance of 20 km. These delays significantly degrade the performances of the LR-PON with the existing centralized dynamic bandwidth allocation (DBA) algorithms. That is why advanced DBA schemes compatible to the LR-PON are required to reduce its longer propagation as well as end-to-end delays. Proper scheduling of the Report and Gate messages is one of the main challenges to design a new DBA algorithm for the LR-PON. Without proper scheduling of the Report and Gate messages, the LR-PON system suffers from over-granting problem. In this thesis, we propose two DBA schemes, i.e., scheme1 and scheme2, for the LR-PON system. The scheme1 is used to reduce the end-to-end packet delay while the scheme2 is used to mitigate the over-granting problem. In the scheme1, the maximum length of a time cycle is subdivided into multiple units called grant processing units and rapidly grants the window size to each optical network unit (ONU). In the scheme2, in the Report message, each ONU sends the frame information instead of total buffer occupancy to avoid the over-granting problem. The combined effect of the scheme1 and scheme2 effectively improves the overall quality of services (QoSs) of the LR-PON system. The performances of the proposed schemes have been evaluated by numerical simulations. The simulation results also have compared with the three existing DBA schemes, i.e., enhance interleaved polling with adaptive cycle time (E-IPACT), multi-thread polling (MTP), and conventional single thread poling (STP), in terms of end-to-end packet delay, bandwidth utilization, over-granting rate, computational complexity, and throughput. It shows that the proposed schemes can ensure the enlargement of the LR-PON system with better QoSs.

Keywords: Dynamic bandwidth allocation Algorithm, scheduled multi Gate polling, multi-thread polling, enhance-interleaved polling with adaptive cycle time, over-granting problem.

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List of Abbreviations

AMGAV	Adaptive Multi-Gate Polling with Void Filling
ASE	Amplified Spontaneous Emission
ATH-DBA	Adaptive Threshold Based Dynamic Bandwidth Allocation
AWG	Array Wavelength Gratings
BWU	Bandwidth Utilization
CO	Central Office
CRC	Cyclic Redundancy Check
DBA	Dynamic Bandwidth Allocation
DBR	Dynamic Bandwidth Request
DC-PGO	Delay-Constrained Periodic Gate Optimization
DeMUX	De-multiplexing
DHSSBA	Dynamic Hybrid Slot Size Bandwidth Allocation
DS	Downstream
DSL	Digital Subscriber Line
DWDM	Dense Wavelength Division Multiplexing
EC	Execution Cycle
EDC	Electronic Dispersion Compensation
EDFA	Erbium-Doped Fiber Preamplifier
E-IPACT	Enhanced Interleaved Polling with Adaptive Cycle Time
EIS	Efficient Inter-Thread Scheduling
EPON	Ethernet Passive Optical Network
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FIFO	First in First Out
FTTB	Fibre to The Building
FTTC	Fibre to The Curb
FTTH	Fibre to The Home
FTTPC	Fibre to The PC

GEM	Generic Encapsulation Method
GPON	Gigabit Passive Optical Network
HOL	Head of Line
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IFG	Inter Frame Gap
ILP	Interleaved Polling
IMTP	Inter Multi-Thread Polling
IP	Internet Protocol
IPACT	Interleaved Polling with Adaptive Cycle Time
IPTV	Internet Protocol Telephony
ITU-T	International Telecommunication Union-Telecommunication
LE	Local Exchange
LL	Logical Links
LLID	Logical Links Identifier
MAC	Medium Access Control
MG-DBA	Multi Group Dynamic Bandwidth Allocation
MPCP	Multi-Point Control Protocol
MTP	Multi-Thread Polling
MUX	Multiplexing
NA+	Newly Arrived Plus
OADM	Optical Add Drop Multiplexer
OAN	Open Access Network
OFDM	Orthogonal Frequency Division Multiplexing
OFDM-PON	Orthogonal Frequency Division Multiplexing Passive Optical Network
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPEX	Operational Expenditure
OSA	Optical Society of America
P2MP	Point-To-Multi-Point
PBO	Prediction Based Online

PGO	Periodic Gate Optimization
PGO-QoS	Periodic Gate Optimization with Quality of Service
PON	Passive Optical Network
QoS	Quality of Service
QR	Queue Report
RG	Rayleigh Backscattering
RN	Remote Node
RSOA	Reflective Semiconductor Optical Amplifiers
S-AMGAV	Synergized-Adaptive Multi-Gate Polling with Void Filling
SARF	Smallest Available Report First
SDH	Synchronous Digital Hierarchy
SLA	Service Level Agreement
SMGP	Scheduled Multi Gate Polling
SOA	Semiconductor Optical Amplifiers
SR+	Subsequent Requests Plus
SSLED	Spectrum Sliced Light Emitting Diodes
STP	Single Thread Polling
T-CONT	Transmission Container Buffers
TDMA	Time Division Multiple Access
TDM-PON	Time Division Multiplexing Passive Optical Network
UAP	User Access Point
US	Upstream
VoIP	Voice over Internet Protocol
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WDM-PON	Wavelength Division Multiplexing Passive Optical Network
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

CHAPTER I

INTRODUCTION

This chapter starts with the introduction of the Passive optical networks (PONs). The over view of PON technologies, standard, and applications are discussed precisely. The aim of the research work with existing problem and its objectives are presented at the end of this chapter.

1.1 Introduction to Passive Optical Network

The PON systems are point-to-multi-point (P2MP) optical networks with no active elements in the signals' path from source to destination. The only interior elements used in such networks are passive combiners, couplers, and splitters. A PON is a P2MP, 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 optical line terminal (OLT) to optical network units (ONUs). The OLT is located at the service provider's central office (CO) and a number of ONUs are located at the near end users. The PON is considered as a promising next-generation access technology to fulfill the high bandwidth demand by the real time data traffic [1]. It is an efficient access network that provides lower operation and maintenance costs and allows larger distance between the CO and end users [2]. Advantages of using a PON for local access networks are numerous [3, 4, 5]:

i. A PON supports longer distances between CO and customer sites. Nearly maximum 5.5 km distance can be supported by using digital subscriber line (DSL), while over 20 km communication distance can be operated by using a PON local loop [6].

ii. The PON provides higher bandwidth due to deeper fiber penetration. Although the fibre-to-the-building (FTTB), fibre-to-the-home (FTTH) or even fibre-to-the-PC

(FTTPC) solutions have the ultimate goal of fiber reaching all the way to the customer premises fibre-to-the-curb (FTTC) may be the most economical deployment today [7].

iii. The PON system reduces the fiber deployment cost in both the local exchange and local loop.

iv. A PON can support video broadcasting in downstream direction because of its P2MP structure.

v. The PON systems can support several of the services such as internet protocol (IP), telephony, IP television (IPTV), video on demand service, video conferencing etc.

vi. The PON offers low cost and high bandwidth solutions in the *last mile* of service of the internet access.

1.2 PON Technologies

The PON is an access technology used by service providers. It relishes a leading position in the global market. It brings optical fiber communication most of the way to the user premises. As the deployment of the PONs grows to serve the multi millions of homes, it can be shown that a new era of access communication technology is coming. In the following subsections, several PON topologies are explained.

1.2.1 Time Division Multiplexing PON (TDM-PON) Techniques

A PON system consists of an OLT placed between the COs node and several number of user nodes, known as ONUs. A shared fiber is used to connect the OLT to several ONUs through a passive optical splitter/combiner [8]. Fig. 1.1 shows the transmission of downstream data packets among all the ONUs through a splitter. A matchless identifier is used for each of the ONU. By getting the broadcasted data, the ONU reads the destination address of each packet and selects the ones that match its address. In downstream, the synchronization among transmissions for different ONUs is straightforward because it is done directly by the OLT. In the upstream direction, a fixed time slot is assigned for each ONU in which data packets are transmitted to the OLT through the combiner [9]. For selecting the upstream time slot by each ONU either static bandwidth allocation or dynamic bandwidth allocation (DBA) is used. In the upstream direction, for better bandwidth utilization and collision avoidance, the PON system uses DBA algorithm [10].

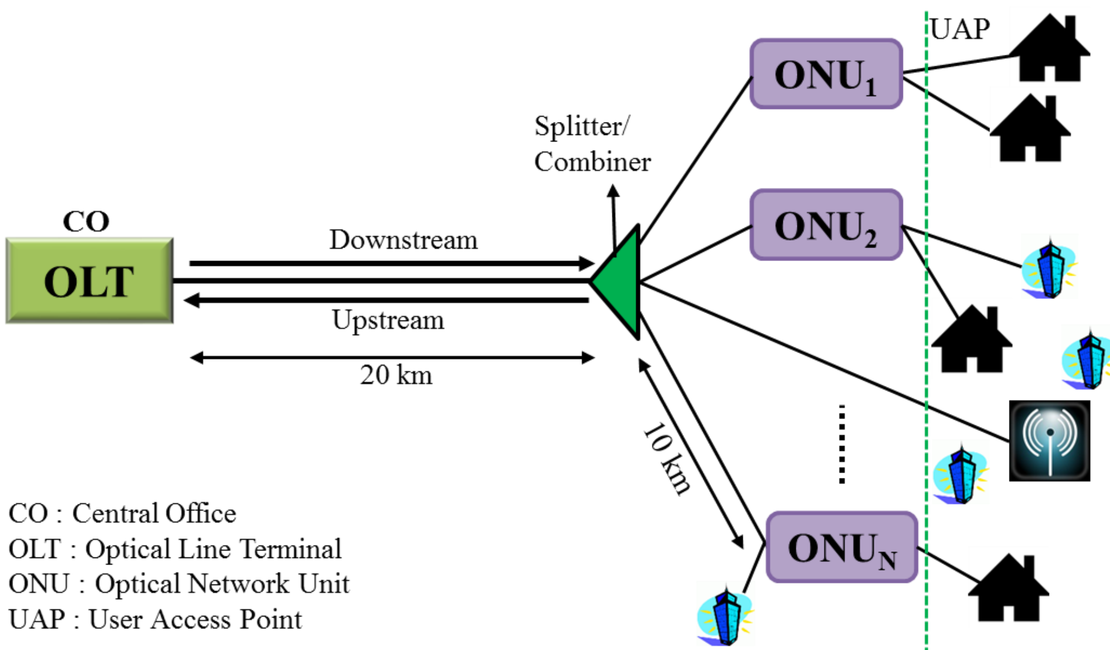

Fig. 1.1 TDM-PON architecture [8].

1.2.2 Ethernet and Gigabit PON Technologies

Two most promising standard of PON technologies are Ethernet PON (EPON) [11] and gigabit PON (GPON) [12]. Nowadays, these two standards are commercially used. Same types of network structure like fully passive optical splitters/combiners, standard 20 km network coverage, P2MP topology are used in both the EPON and GPON. Both the EPON and GPON technologies provide a wide bandwidth and variety of services to the user access point (UAP). The split-ratio is variable between 16 to 64 users. However, different medium access control (MAC) protocols and data encapsulation methods are used in the EPON and GPON systems. While the EPON carries bursts of pure Ethernet frames, GPON encapsulates data using Generic Encapsulation Method (GEM) [13]. The basic frame transmission process of GPON and EPON are shown in the Figs. 1.2 and 1.3, respectively [14]. Comparison between the EPON and GPON is given in Table 1.1 [15, 16].

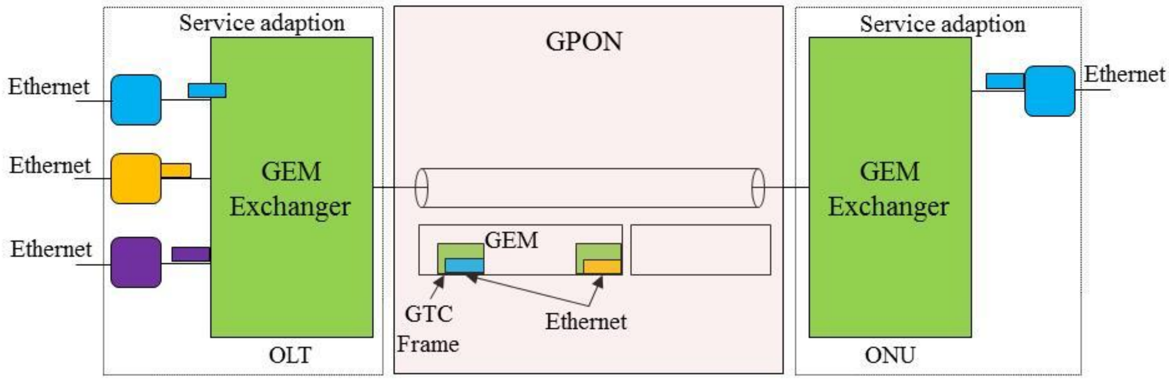

Fig. 1.2 Basic framing structure of GPON [14].

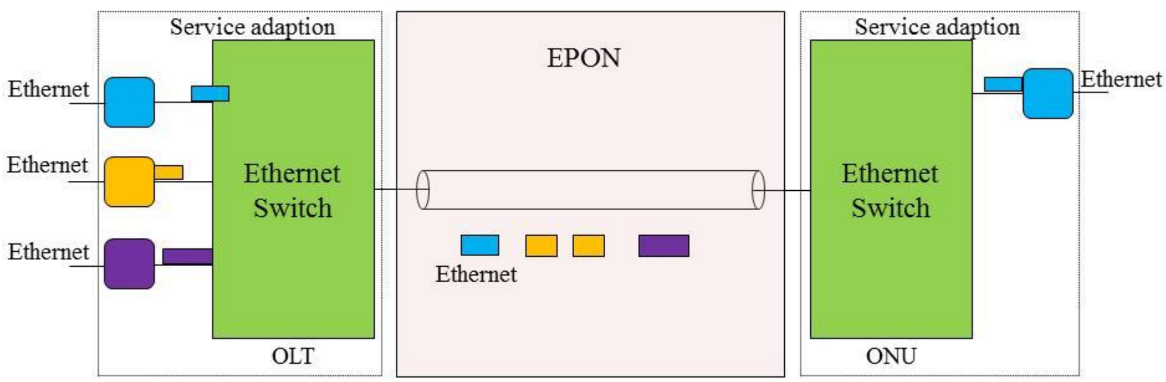

Fig. 1.3 Basic framing structure of EPON [14].

1.2.3 Wavelength Division Multiplexing PON

Wavelength division multiplexing PON (WDM-PON) is the solution to increase the split ratio, the number of network users, and the offered bandwidth for the next generation access network [17]. Fig. 1.4 shows the typical structure of the WDM-PON system. A virtual P2MP connection among the OLT and several ONUs are established by the WDM configuration; where, different wavelengths are assigned for different ONUs for transmission of data without any interference.

Table 1.1 Comparison between the EPON and GPON standards

Topic	***EPON***	***GPON***
Standard	IEEE 802.3 ah	ITU G.984
Downstream (DS) line rate	1.25 Gbps	1.24416/2.48832 Gbps
Upstream (US) line rate	1.25 Gbps	1.24416 Gbps
Bandwidth allocation overhead	64 byttes	2 bytes
DS/US wavelengths	1490 / 1310 nm	1490 / 1310 nm
Frame size	64 to 1518 bytes	5 bytes (GEM); <1518 bytes
Split ratio	1:16 / 1:32	1:32 / 1:64
Communication distances	10-20 km	10-20 km
Maximum data rate	2.5 Gbps	1 Gbps
MAC framing	Ethernet	GEM
DBA granting unit	MPCP Gate frame	GTC Overhead
DBA control unit	LLID	T-CONT
DBA reporting mechanism	Separate Report frames	Embedded OAM

The major difference between the implementation of the WDM-PON and TDM-PON is that the WDM-PON employs a WDM device in the ONU such as array wavelength gratings (AWG) instead of a power splitter. Besides other more complex functionalities like the wavelength routing function, this component allows to multiplex or de-multiplex different wavelengths. For selecting as well as splitting the wavelength the AWG is used. To separate the upstream and downstream transmission channels signals of different wavelength ranges are used. This configuration reduces the power loss significantly and consequently supports a large number of ONUs as well as end users. [18]. A specific wavelength is assigned into each of the port of the AWG; this specific port is used for transmitting data from ONUs to the OLT.

Fig. 1.4 shows the basic architecture of the WDM-PON. In WDM-PON, the OLT is required to install a standard receiver and a wavelength de-multiplexing device. Upstream transmission in a WDM loop back structure is achieved by utilizing a single or two fiber links. In the case of a single fiber link, bidirectional transmission of the light and the modulated signal leads to Rayleigh backscattering (RB) noise. This issue affects the performance of downstream and upstream transmissions and consequently degrades the transmission distance and the receiver sensitivity [19, 20].

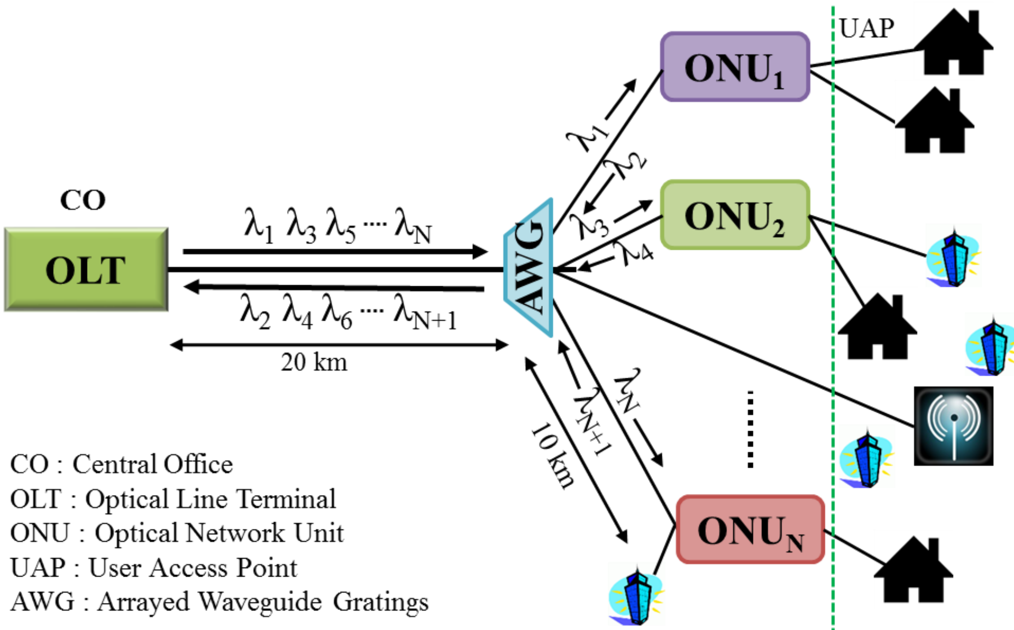

Fig. 1.4 WDM-PON architecture [17].

1.2.4 Orthogonal Frequency Division Multiplexing PON

Orthogonal frequency division multiplexing PON (OFDM-PON) constitutes other types of PON technology. The OFDM is a modulation scheme and that can provide superior transmission capability by increasing the bandwidth provisioning of optical access networks (OAN). OFDM uses a large number of closely spaced orthogonal subcarriers to carry data traffic. Each subcarrier is modulated by a conventional modulation scheme (such as quadrature amplitude modulation or phase-shift keying) at a low symbol rate, thus achieving the sum of the rates provided by all subcarriers compatible to those of conventional single-carrier modulation schemes in the same bandwidth. Since the data rate carried by each subcarrier is low, the duration of each symbol is relatively large. Thus, the inter-symbol interference can be efficiently reduced in a wireless multipath channel [21]. In optical communications, the dispersions including chromatic dispersion and polarization mode dispersion have similar effects as those of multipath. Therefore, employing the OFDM modulation scheme in the OAN can greatly increases the network data rate and reach.

The OFDM-PON has same architecture as the conventional PON and uses one wavelength for downlink and another wavelength for uplink. Fig. 1.5 shows that, there is *N* ONUs at the end-users in this OFDM-PON. The OLT generates multiple orthogonal subcarriers by using inverse fast Fourier transform (IFFT). This process is called OFDM modulation. The OLT allocates a number of orthogonal subcarriers for each ONU, since the whole OFDM bandwidth is divided into *N* sub-bands. These orthogonal frequencies are up-converted

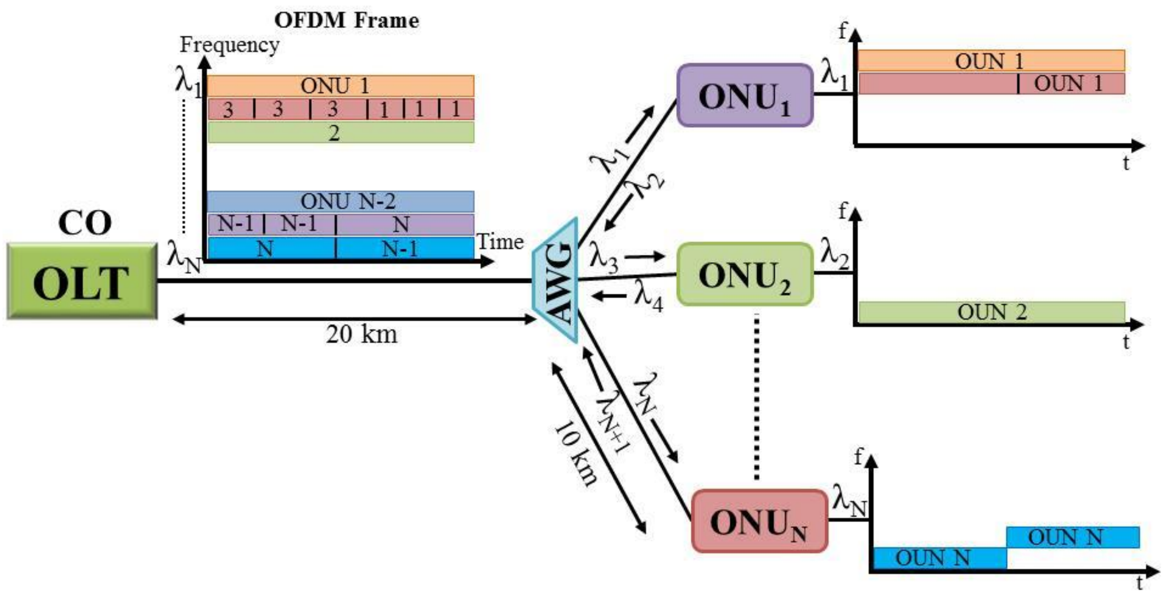

Fig. 1.5 OFDM-PON architecture [21]

over optical carrier wavelength and then propagated along a single optical fiber. The downlink signal is split at the RN into *N* signals by using the passive splitter or combiner. Each ONU receives all the downstream signals and picks out its assigned subcarriers. The fast Fourier transform (FFT) is used at the receiver of ONU to produce the original transmitted data. This process is called OFDM demodulation. In the upstream direction, each ONU generates a number of orthogonal subcarriers according to the available allocated bandwidth. The bandwidth is allocated and controlled by the OLT [22, 23].

1.3 Applications of PON Technologies

It supports the rising demands of high bandwidth, high speed, and real time data communication with larger number of users and more coverage areas in the PON based access networks. The FTTH is a long term solution for supporting large number of users with several services that is economically implemented by the PON system. The Applications of PON systems are given below;

i. **Internet protocol (IP) over PON:** A greater number of IP traffic is supported by the current and planned access systems. The modern EPON and GPON systems are designed to transport variable sized IP traffic that is terminated in a packet router in the CO. Voice over internet protocol (VoIP) and IPTV have greater applications in the modern technology [24].

ii. **Triple play and quadrature play:** Video, voice, and high speed internet services on a single access system are considered as the triple play service. When this triple play service is extended into wireless communication system that is called quadrature play service [25, 26]. The triple play network hires different devices for different services and requires a dedicated balance among the demands.

iii. **Multimedia conferencing and shared environment:** Similar to the triple play service, multimedia conferencing combined several media services. However, this service requires better synchronization of these media elements. PON access systems support acceptable capacity for this multimedia application. The PON technology introduces large screen and high definition video window system applications for online conferencing [27]**.**

iv. **Backhaul services:** When remote traffic aggregation points are connected to the metropolitan backbone network that referred as the backhaul services. The advantages of PON based backhaul network are as follows [26]:

- Bandwidth flexibility is on demand based.
- Network scalability requirements are grown.
- Larger capacity than the convention PON system.

v. **Cloud-based Services:** When multiuser computational resources distributed the network instead of maintaining the private resources such as a dedicated corporate database or server is considered as the cloud computing [28]. In heart, cloud computing enables the provisioning of virtual resources. The PON based cloud computing greatly concerns about the security and privacy for reducing the vulnerability of limitations on access or performance due to the adverse network conditions, whether malicious or natural.

1.4 Long Reach Passive Optical Network (LR-PON)

With the rising demands of high bandwidth, high speed, and real time data communication for supporting larger number of users and increasing coverage areas in the PON based access network. To make better system performance with limited capital expenditure fusion of the node is required where single CO is operated instead of multiple COs in long coverage area. The extension of coverage area of the PON system from 20 km to 100 km reach is known as LR-PON [29].

The LR-PON networks can be deployed in a ring-and-spur architecture where the ring topology is used to increase the network resilience in case of a failure while at each node on the ring an optical add drop multiplexer (OADM) is placed shown in Fig. 1.6. There are a number of PON architectures proposed in the literature based on the LR-PON concept including the hybrid PON [30] and Super PON [31]**.**

A general LR-PON architecture consolidates the multiple head end devices known as OLTs, which were located at the local exchange (LE) within PONs, and the CO. Fig. 1.6 shows the ring and spur architecture of the LR-PON. Here, several remote nodes are connected with each other by optical fiber to distribute the traffic in various directions by using WDM ring. Basically, the P2MP PON architecture consists of an OLT in the CO to distribute the upstream bandwidth among the ONUs. A passive 1: *N* splitter or combiner is used to connect a single OLT and *N* number of ONUs in the LR-PON.

The LR-PON system makes OANs smarter and more feasible with greater uses facilities in the view of economic consideration as well as services. The extension of the reach of the

PON based access network reduces the operational cost by unifying the multiple COs. It also allows a cost reduction of the system by using an expensive technology in the shared section of the network, such as at the OLT or at the RN to ONU. However, the LR-PON is introduced to cover large scale geographic area in a cost effective way, its new features and configuration can introduce many new research challenges. Some of the research challenges and solutions of them are discussed in the Section 2.9.

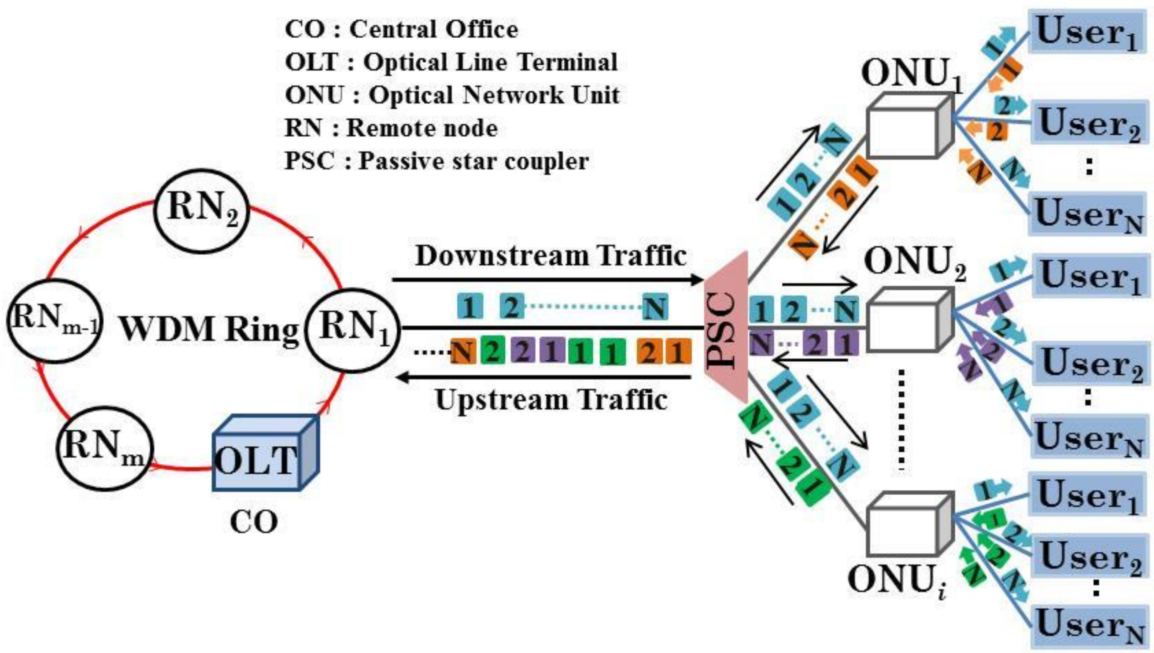

Fig. 1.6 Ring and spur architecture of the LR-PON.

1.5 Dynamic Bandwidth Allocation (DBA) Algorithm

In modern optical communication systems various types of PON systems are existed. Among them the EPON system is considered as one of the preeminent communication technologies [32]. In the downstream direction, the EPON system broadcasts all data signals to the ONUs. However, a sophisticated bandwidth allocation algorithm is required for the upstream data transmission to avoid the data collisions from various ONUs. The DBA algorithm is used to calculate the granted window size for each of the ONU. Recent researches have focused on enhancing the performance of DBA algorithms in the LR-PONs [33]. The important features of the DBA algorithms for the PON systems are;

i. Avoid collision among the data packets of different ONUs in the upstream transmission.

ii. Improvement of system performance due to signaling message delay.

iii. Different classes of services are performed by DBA algorithm.

iv. Provide effective bandwidth distribution according to the request of the ONUs.

1.5.2 DBA Solutions Techniques for EPON

Wavelength assignment in the grant scheduling process is the most challenging issue for bandwidth distribution in WDM-PONs. Two problems are identified for DBA assignment considering WDM-PON. Firstly, grant sizing that denotes the amount of bandwidth to be assigned to each ONU, and secondly, grant scheduling that stands for the time and wavelength to transmit data. It seems that in practical to consider an EPON to assign wavelengths based on first-fit or random assignment fashions. The researches have also proposed to run hybrid online and offline scheduling for EPONs where a group of ONUs can be scheduled offline while the rest can be scheduled with respect to the online next available supported channel fashion so that reduced delay and enhanced utilization can be obtained [34 - 37].

1.6 Research Objectives

To propose a new MTP based DBA algorithm that can reduce the end to end delay compared to the existing algorithms. Because, the conventional MTP based DBA algorithms suffers from longer end–to-end delay for the LR-PON system due to large number of idle times between two successive data transmission time and indecorous report-grant scheduling scheme.

To derive the mathematical model of multi-thread polling (MTP) based DBA algorithms with proper bandwidth allocation scheduling process and observe the performance of the LR-PON system for various offered load and cycle time.

The MTP based DBA algorithms inherently suffers from the over-granting problem that significantly degrade the overall performance of the LR-PON system. To reduce the over-granting problem the new DBA scheme is introduced.

To reduce the overall computational complexity only OLT based DBA processed scheme is introduced. Whereas the conventional enhance interleaved polling with adapted cycle time (E-IPACT) scheme can mitigate the over-granting problem but it increases the algorithm's complexity.

To improve the bandwidth utilization and throughput for heavily loaded ONUs in the LR-PON system.

1.7 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 presents the architecture of the LR-PON technologies and their challenges. This chapter also elaborates the basic principle of the DBA algorithms for EPON system and how the DBA algorithms overcome the respective challenges of the LR-PON system.

Chapter 3 elaborates the literature review of recently proposed MTP based DBA algorithms for the LR-PON system. Here, we also discuss about the limitations of these existing schemes for deploying the LR-PON system.

Chapter 4 presents the proposed "Scheduled Multi Gate Polling (SMGP) Algorithm for Delay Reduction of the LR-PON based Access Network". This scheme is used to reduce the average packet delay.

Chapter 5 presents the principle of the mitigation of over-granting problem for the LR-PON system to achieve better QoSs. This chapter also elaborates the effects of over-granting problem on the MTP based DBA algorithms.

Chapter 6 illustrates the simulation results and performance analysis of the proposed MTP based DBA scheme compared to the existing MTP based DBA schemes.

Chapter 7 concludes this thesis works and confers the directions for future work.

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CHAPTER II

LR-PON ARCHITECTURE AND PRINCIPLE OF DBA ALGORITHMS

This chapter presents the detail configuration of the LR-PON based access networks and its architecture. It describes the research challenges of the deployment of LR-PON system. This chapter also presents the precise explanation of the DBA schemes for the LR-PON. Finally, the signaling protocol and principle of the DBA algorithms for the LR-PON are explained.

2.1 Introduction to the LR-PON

The span of a broadband access network using the PON technology can be increased from today's standard of 20 km to 100 km or higher. Such an extended-reach PON is known as the LR-PON [1].

There has been growing interest in the study of the advanced bandwidth distribution algorithms for reducing end-to-end packet delay in the LR-PON based OAN. The interesting point of the PON is that it decreases the cost by reducing number of active equipment in the network. The rapid growing of PON based OAN induces difficulties to manage large number of users in a long coverage area. The increasing number of users as well as network size also increases the number of network equipment such as splitters, connectors, splices, COs, and access nodes in the conventional short range PONs. Consequently, the overall installation, maintenance and operational expenditure (OPEX) are also going high. That is the reason to deploy the LR-PON system, where 20 km span of short range PON is enlarged to over 100 km long distance OAN.

The recent research on OAN has been introduced several developments in the area of optical networking and coding. Some of the advanced technologies are WDM, optical amplification, OADM, and high-speed switching have found their way into the wide area network (WAN), resulting in a substantial increase of the communications backbone capacity and greatly improved reliability with protection mechanism [2].

2.2 LR-PON Architecture

A general LR-PON architecture is composed by an extended shared fiber connecting the CO and the local user exchange, and optical splitter connecting users to the shared fiber. Compared with the traditional PONs, the LR-PON consolidates the multiple OLTs and COs where they are located, thus significantly reducing the corresponding OPEX of the network. By providing extended geographic coverage, the LR-PON combines optical access and metro into an integrated system. Thus, cost savings are also achieved by replacing the synchronous digital hierarchy (SDH) with a shared optical fiber. In general, the LR-PON can simplify the network by reducing the number of interfaces equipment, network elements, and even number of nodes [3].

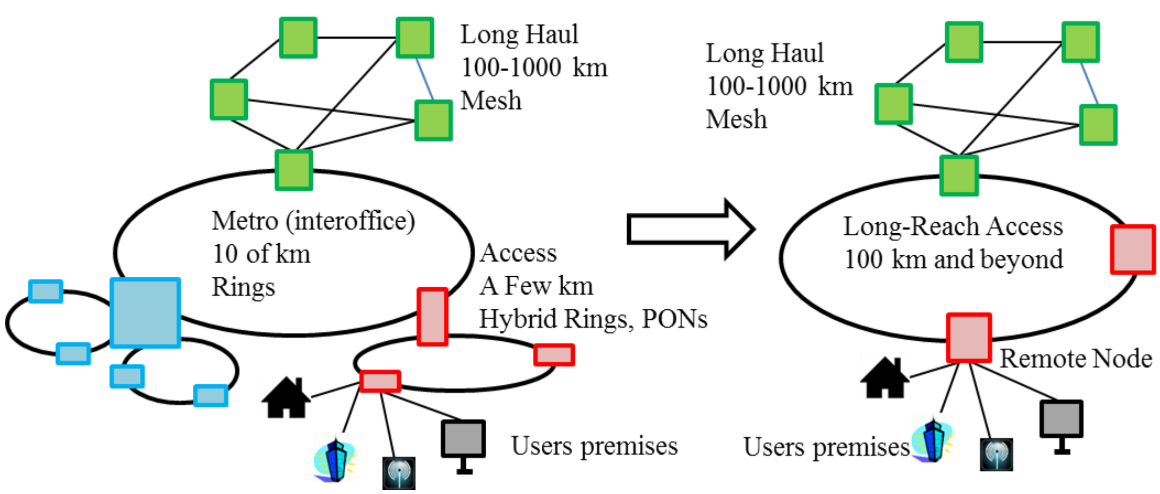

Fig. 2.1 LR-PON simplifies the telecoms network [3].

Although the idea of extending the reach of a PON has been around for quite a while, it is emphasized recently because the optical access is entering quickly into residential and small business markets and the simplification of telecom network requires architecture to combine the metro and access networks. Fig. 2.1 shows how the LR-PON simplifies the telecom network. The traditional telecom network consists of the access network, the metropolitan area network, and the backbone network (also called long-haul or core network) [4]. However, with the maturing of technologies for long-reach broadband access, the traditional metro network is getting absorbed in access. As a result, the telecom network hierarchy can be simplified with the access point end close to the backbone network.

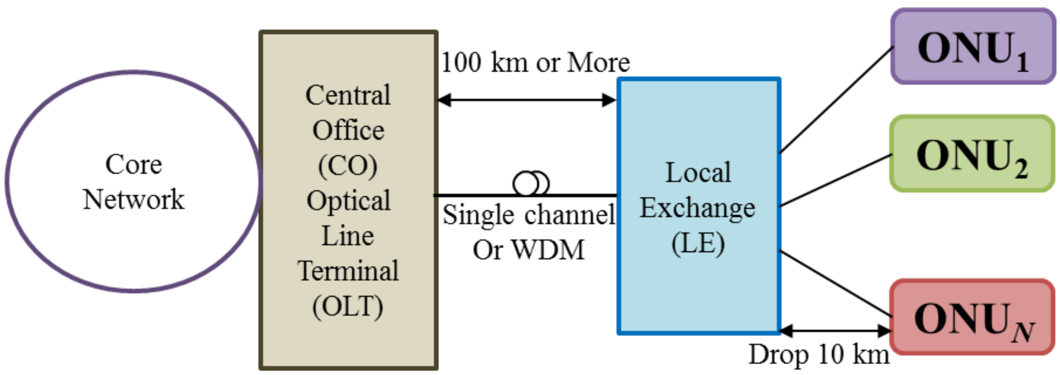

Fig. 2.2 LR-PON basic architecture [5].

Fig. 2.2 shows the basic architecture of a LR-PON system. The OLT connects the core network and the access network [5]. The local exchange resides in the local user's premises that are close to the end customer. The optical signal propagates across the fiber forming the feeder section 100 km or upper with the CO and the local exchange at its two ends. And then the fiber is split and connected to a large number of ONUs. In order to compensate for the power loss due to long transmission distance and high split size, optical amplifiers are used at the OLT and the local exchange.

2.3 Reach Extension of a DWDM GPON to 135 km

135 km network architecture is demonstrated successfully in [6]. The proposed network architecture is based on a 135 km branch and tree structure, composed by a 125 km of fiber between the CO and the LE and by another segment of fiber to 10 km between the LE and each ONU. In the first part of the network, between CO and LE, a dense wavelength division multiplexing (DWDM) system is used. In the second part of the network, between LE and

each ONU, a single fiber segment is installed. This architecture, shown in Fig. 2.3, can support 2560 users through a DWDM system with 40 optical channels and a splitting factor of 1:64 for each PON. The length of fiber between the bespoke transponder and the farthest ONU was increased to 20 km and the total split was reduced to 32.

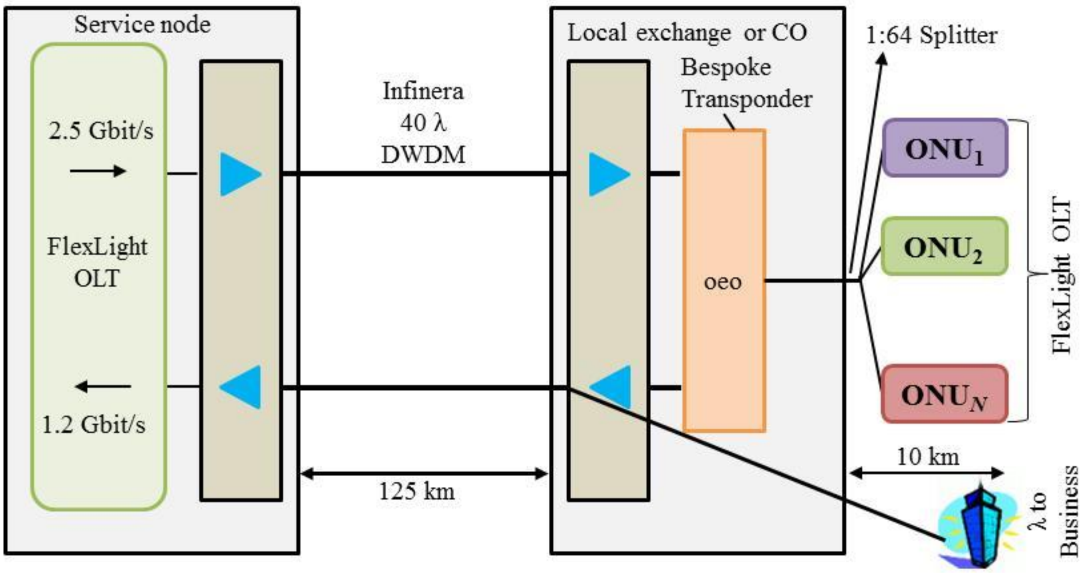

Fig. 2.3 Network architecture of GPON extended to 135 km via DWDM [6].

The high degree of optical component integration shown in the DWDM system could be used to significantly reduces the footprint of access and metro equipment. In the system demonstrated, each wavelength can support a split of 64, so that a fully populated system could support 2560 ONUs. This provides the opportunity to greatly simplify network designs and reduce costs, which will be essential as bandwidths increase [6].

Due to the reach extension for bidirectional optical transmission over a single fiber, the system's performance could be degraded by the in-band crosstalk produced with double RBs within an optical fiber and optical amplifier for bidirectional gain [7].

This hybrid WDM-TDM based LR-PON system interconnects the WDM-TDM PON architecture with mesh links between AWGs in service areas is feasible when using the proposed waveband MUX- DeMUXs. Moreover, the use of mesh links between AWGs helps to reduce the fiber installation and maintenance costs of long-reach access networks since it avoids unnecessarily long fibers between COs and service areas. Some of the advanced LR-PON architectures were presented in [8] to reduce the operational cost and upgrade the system performance by utilizing the high split ratio and optical amplifier.

2.4 Research challenges of the LR-PON

The survey of the LR-PON architectures shows that there have great scopes of improvement in the field of physical layer for transmitting data in the long distance communication. The operational cost of the LR-PON deployment is achieved by the emerging researcher in the physical layer that can introduce a splitter with high splitting ratio, automatic gain control (AGC) optical amplifier, reflective semiconductor optical amplifier for bidirectional PON system, optical fiber based amplifier, e.g., EDFA, and highly configured arrayed wave guide for WDM system [9, 10, 11].

The shift from PONs to the LR-PONs translates into longer propagation delays from the OLT to the ONUs. But the expansion of access network to 100km increases the propagation delays from 200 μs, i.e., 20km reach PON, to 1ms, i.e., LR-PON [12]. So more sophisticated and efficient grant scheduling schemes are required while taking care of the imposed propagation delay. Most of the previous studies on delay analysis for PONs have focused on ordinary PONs which normally spans less than 20 km [13]. The recent research progress shows that advanced bandwidth distribution scheme is required to overcome the challenges of larger propagation delay in the LR-PON. A variety of research challenges in this field are discussed in bellow:

i. The LR-PON produces large propagation delay that may appreciably increase the overall transmission delay when conventional DBA algorithms are used. Proper scheduling of the Report and Gate messages is one of the main challenges to design a sophisticated DBA algorithm for the LR-PON [12, 13].

ii. Without proper management of the Report and Gate messages, the LR-PON system suffers from over-granting problem [14].

iii. Conventional polling imposes a critical second constraint on the downstream transmission of Gate messages; they may not be transmitted before the arrival of the Report message to the OLT. Since the OLT cannot generate a Gate before receiving a Report the cycle duration in conventional polling cannot fall below. This feature is the crucial limitation of conventional polling schemes [13, 14].

iv. The over-granting problem occurs when the DBA scheme allocates a larger timeslot size than actually needed by the ONU. Over-granting problem that is inherent in several MTP based DBA algorithms, especially when applied to the LR-PONs [15].

2.5 Principle of DBA Algorithms

In the PON system, DBA algorithm is the key mechanism by which upstream packets are scheduled and allocated for each of the ONUs. While the majority of end user's bandwidth is currently downstream traffic, new services such as video conferencing, IP telephony, and IPTV, require increased upstream bandwidth. For this reason, maximizing the bandwidth of upstream traffic and reducing its latency is essential for network operators to maximize revenue [16]. In the LR-PON systems, the increased propagation delays are inherent due to the longer distances because greater packet delays [17]. In addition, the larger propagation delays also affect the DBA mechanism by introducing additional delays which also increase packet latency. For this reason, it is essential to study how to standardized DBA algorithms when the physical reach of the network is increased. This will assist network operators plan for the future when longer reach PONs may be deployed. The main features of the DBA algorithms in the EPON systems are [18];

- Grant scheduling framework
- Grant sizing
- Grant distributing
- Utilizing the bandwidth properly

In bidirectional PON system that means both downstream and upstream traffics are communicated through a single communication link. In downstream direction, the OLT broadcasts traffic packets to the entire ONUs. But each of the ONU send only own user's data packets to the OLT in upstream direction. This is concerning issue because *N* numbers of ONU send data to the OLT through a single optical fiber link can cause a collision between the upstream packets of multiple ONUs. So, DBA algorithms are necessarily used for transmitting data in organizing way to avoid any collisions in the upstream transmission. The DBA that operates at the OLT is based on the statistical multiplexing among the ONUs. The OLT requires instantaneous bandwidth requirement information from each ONU to make access decisions [19]. In the EPON standard, logical queues are referred to as logical links (LL) represented by an LLID. To assign bandwidth in EPON, DBA is done on per LLID basis. In general, for both the EPON and GPON, the requirement of the DBA is to provide efficient bandwidth utilization in the shared upstream channel while ensuring that each logical queue is allocated bandwidth according to its QoS requirements [20]. Taxonomy for the DBA algorithms is shown in Fig. 2.4.

2.6 DBA Algorithm Framework for the EPON

A framework for the DBA algorithms of the EPON is shown in Fig. 2.5 [21]. The centralized approach is one which is completely an OLT based bandwidth allocation algorithm. As OLT has the complete knowledge about the whole network and it is easy for OLT to decide on different issues about the networks. Bandwidth allocation is one of the most important among these issues. Whereas in the decentralized approach the scheduling algorithm can either run on the OLT side or on the ONU side. By making bandwidth allocation decentralized the burden of OLT can be reduced while the burden of ONUs is increased. The decentralized approach can be either inter-ONU scheduling or intra-ONU scheduling [22].

In the intra-ONU scheduling, the ONU assigns a weighting factor to each queue, and tracks aggregate ONU service via a global virtual time. Upon arrival of packets at an empty queue the head-of-line (HOL) packets start and finish times are updated whereas packets arriving at a non-empty queue are simply buffered. Therefore, the queue with the minimal HOL start time

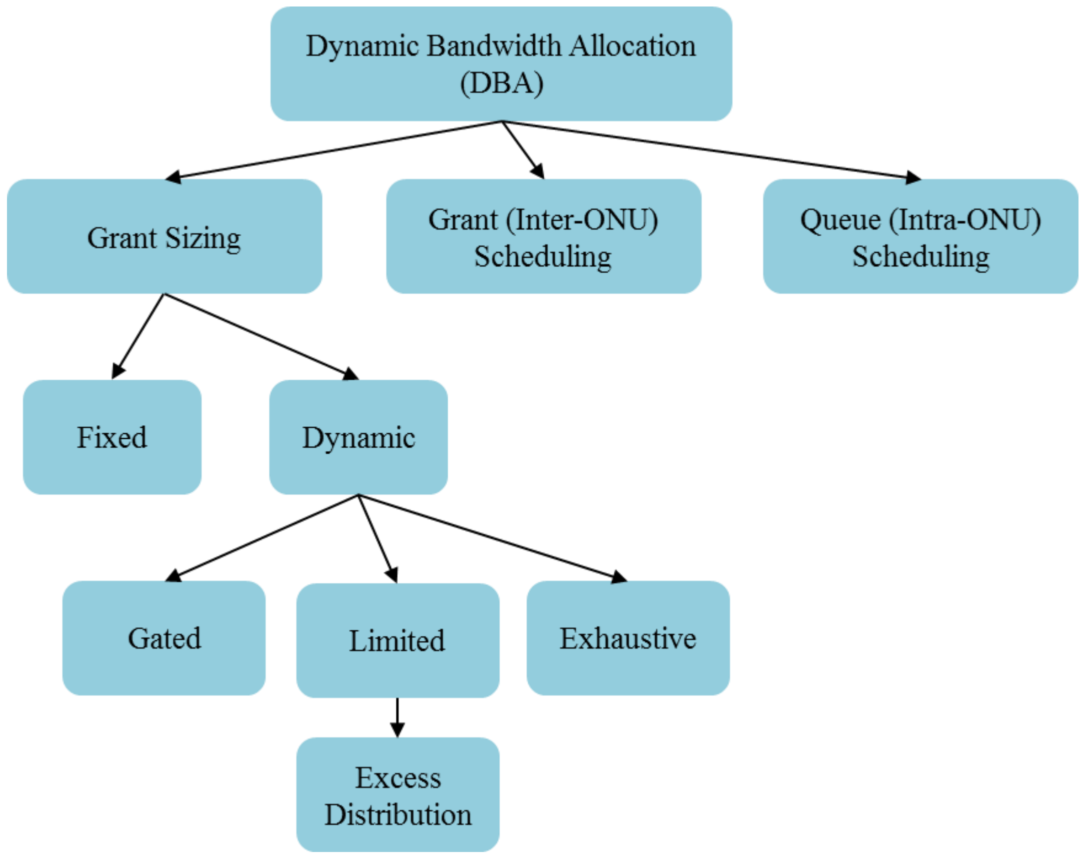

Fig. 2.4 Taxonomy of the DBA algorithms [21].

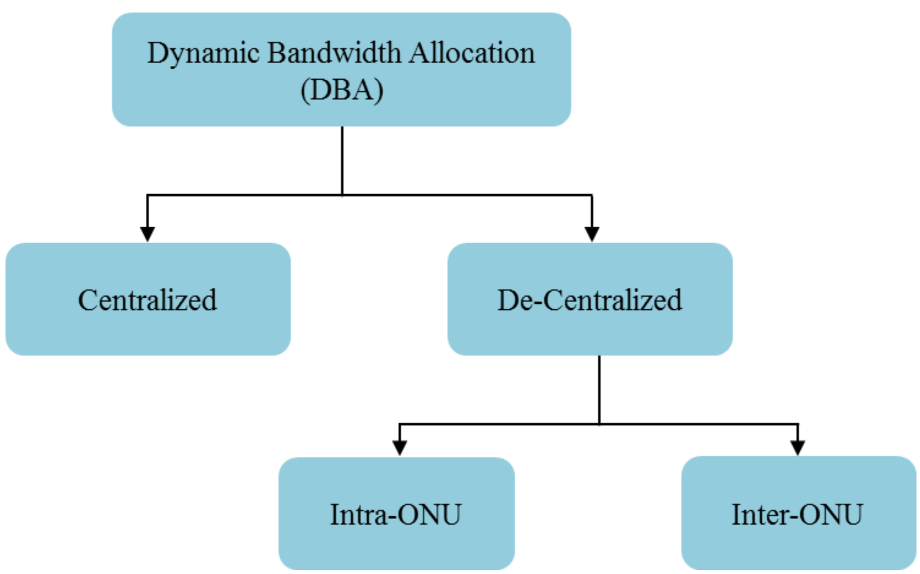

Fig. 2.5 DBA framework for the EPON system [21].

will be selected for the transmission. In the inter-ONU scheduling, it exploits the Report-GATE mechanism for the EPON. Each ONU uses Report message to inform the OLT about its required window size (in bytes) for data transmission. Rather than just reporting the buffered data size as most of the previous DBA algorithms emphasized, each ONU send two requests in the Report: Maximal and minimal window size requirements [22]. The process of intra and inter ONU scheduling for the DBA scheme is shown in Fig. 2.6.

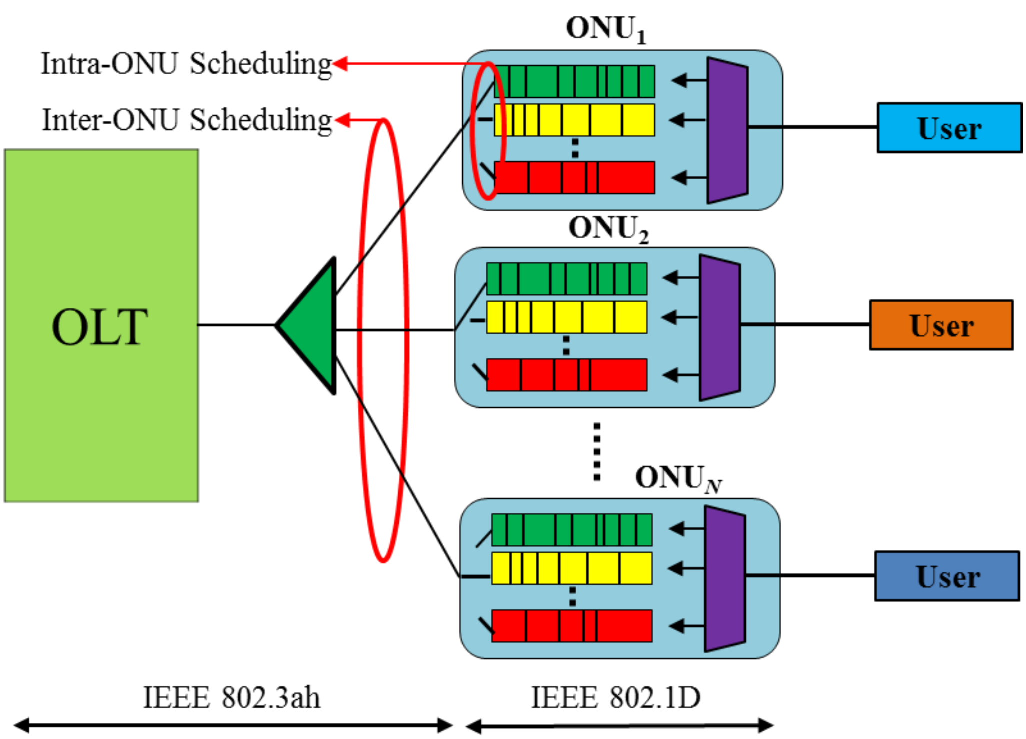

Fig. 2.6 Intra-ONU and inter-ONU DBA scheduling process [23].

2.7 MPCP Format for the Dynamic Hybrid-Slot-Size Bandwidth Allocation Algorithm

A new dynamic hybrid-slot-size bandwidth allocation (DHSSBA) algorithm is proposed in [24] with new Report and Gate message formats to make intelligent bandwidth allocation decisions. 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 high priority (HP) data traffic in the first half cycle and other Gate message is used to assign bandwidth to the best effort (BE) data traffic in the second half cycle.

Following steps are used to illustrate the multi-point control protocol (MPCP) Gate and Report messages scheduling algorithm according to the DHSSBA scheme. From the higher 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. 2.7 shows the diagram of the MPCP Gate message transmission in the proposed scheme.

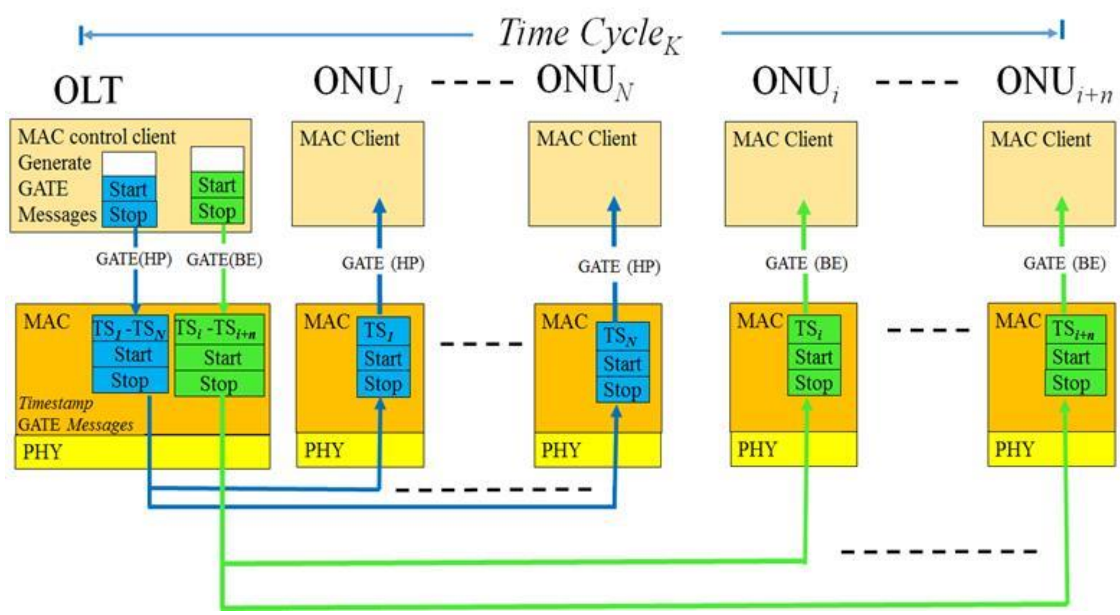

Fig. 2.7 MPCP GATE operation according to the DHSSBA scheme [24].

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 Fig. 2.7, 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 data 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.

2.8 DBA Algorithm Organizing Process

To organize the upstream bandwidth allocation using DBA algorithm in the EPON system, two types of messages are used for controlling the order of request and grant schedule. These messages are identified by Report and Gate message, where Report message is used for requesting the data length sent from ONU_i to the OLT and Gate message is used for granting the amount of allocated data packets to be sent from the OLT to ONU_i.

To facilitate the DBA algorithm and arbitrating the upstream transmission of multiple ONUs of the EPON, the MPCP is standardized by IEEE 802.3ah. Besides auto-discovery, registration and ranging, i.e., round trip time (RTT) computation, operations for newly added ONUs, MPCP provides the signaling infrastructure for coordinating the data transmission from the ONUs to the OLT. The MPCP specifies the mechanism between an OLT and ONUs connected to a P2MP PON segment to allow efficient transmission of data in the upstream direction. There are two modes of operation of MPCP [25];

Auto-discovery (initialization): Auto-discovery mode is used to detect newly connected ONUs and learn the RTT delay and MAC address of that ONU, plus maybe some additional parameters yet to be defined.

Normal operation: Normal mode is used to assign transmission opportunities to all initialized ONUs. It is important to notice that MPCP is not concerned with particular bandwidth-allocation schemes; rather it is a supporting protocol necessary to deliver these decisions from the OLT to the ONUs. The operation of normal mode is described in below;

The overall Report and Gate message scheduling process can be defined as the following steps:

i. Each ONU sends a Report message to the OLT containing the amount of byte length that the ONU wants to transmit.

ii. After collecting all ONU's Report messages, the OLT calculate the amount of byte length using DBA algorithm which can be sent to the ONU_s, this process is called Offline polling. In online polling, OLT calculates the amount of byte length using

DBA algorithm just after receiving the Report message from an ONU and send Gate message to that ONU.

iii. After getting the Gate message, an ONU sends data byte equal to the grant size of the data length with next Report message.

Fig. 2.8 shows the schematic diagram of a DBA scheme for scheduling the upstream data from various ONUs in an EPON system. The DBA processes exactly calculate the starting and ending times of a packet transmission. Data packets of next ONU are transmitted after the end time of the transmission of data packet from current ONU. This is the process of avoiding collusion among the data packets of multiple ONUs in the upstream channel.

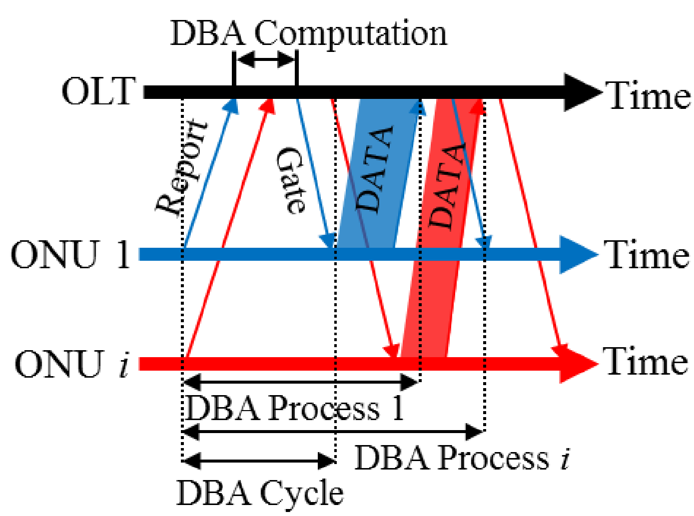

Fig. 2.8 Schematic diagram of a DBA scheme of EPON system.

The above description represents a framework of the protocol being developed for the EPON. There are many more details that remain to be discussed and agreed upon. This work is currently being conducted in the IEEE 802.3ah task force [26].

2.9 Chapter Summary

The LR-PON system ensures the coverage of large geographical area with large number of users to the OANs. Various network structures are proposed to deploy the LR-PON system. Several new optical components are used such as optical amplifier, high split ratio splitter, semiconductor optical amplifier, AWG etc. This chapter also highlights the research challenges of the LR-PON system. The longer propagation delay due to the long distance communication is one of the difficult challenges. The main purpose of the DBA schemes are to make it sure that there should be no collision in the upstream transmission and also have to ensure the QoSs, i.e.,packet delay, queuing delay, packet loss. So, sophisticated DBA algorithm is required to overcome these challenges and make the LR-PON system superior.

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CHAPTER III

LITERATURE REVIEW OF DYNAMIC BANDWIDTH ALLOCATION ALGORITHMS

This chapter presents the precise explanation of the DBA schemes for the LR-PON. The main features of several DBA schemes for the LR-PON, the control messages scheduling scheme, and major limitations of these DBA schemes for the LR-PON are also presented in this chapter.

3.1 Conventional DBA Algorithms in EPON

One of the most well-known conventional DBA algorithms for the EPON is the interleaved polling with adaptive cycle time (IPACT) algorithm [1]. In the IPACT scheme, the OLT polls and grants the upstream bandwidths for the ONUs cyclically in interleaved style. The polling cycle is defined as the time between two successive report messages sent from the same ONU to the OLT. In the IPACT scheme, the polling cycle is variable and adapts to the instantaneous bandwidth requirements of the ONUs. The IPACT scheme is a single thread polling (STP) based DBA algorithm. So, in a time or DBA cycle, the OLT gets only one Report message from the ONU.. Fig. 3.1 shows the exchange of control messages in the STP based DBA algorithm. The conventional polling of ONUs, requires that the OLT must inform the i^{th} number of ONU of grant information, including the start time and the size of the granted window, during or before the time that the previous ONU is transmitting Ethernet frames in the upstream direction. For efficient bandwidth utilization, the grants for i^{th} ONU must be received before the data transmission of the previous ONU is completed and the transmission slots must be scheduled in such a way that the first bit from the i^{th} ONU arrives at the OLT right after the OLT receives the last bit from the previous ONU. This algorithm is the most commonly used together with the limited service (LS) scheme. Under this LS scheme, the window size granted by the OLT to an ONU is equal to the requested window size by that ONU in the Report message of previous time cycle, which is upper bounded by the maximum limit. This maximum limit is needed in order to limit the length of a polling cycle and to avoid bandwidth hogging by greedy ONUs. This scheme efficiently shares the bandwidth among the ONUs while maintaining fairness.

This algorithm can avoids collision among the upstream data transmission of different ONUs for the 20 km standard EPON system. But this process makes a large amount of delay for medium traffic loads. As shown in the Fig. 3.1, there is a huge space or idle time between two successive data transmission windows of an ONU. This void time is existed in the STP scheme that severely degrades the performance of the LR-PON compared to the conventional PON system. In this algorithm, the response time is increased due to the extended reach of the LR-PON that results overall performance degradation [2].

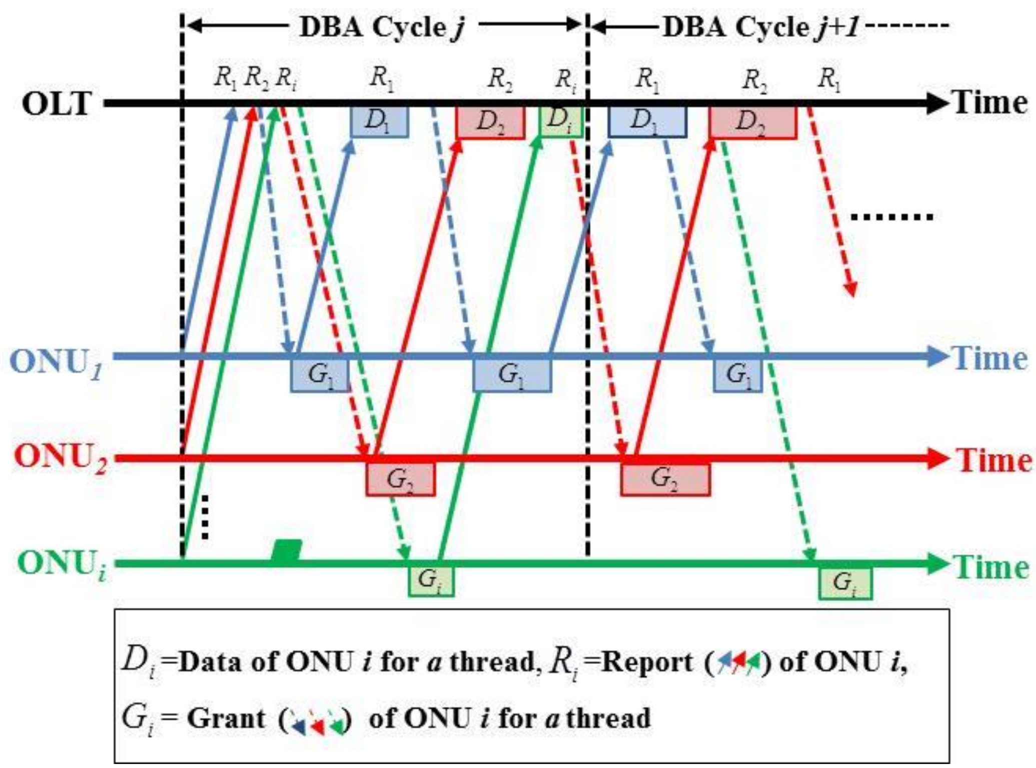


Fig. 3.1 Exchange of control messages in the conventional DBA scheme.

3.2 Multi Thread Polling (MTP) Based DBA Algorithms

One of the main challenges of deployment of the LR-PON system is the longer propagation delay. Specially, the performance of the LR-PON system degraded significantly when the conventional STP based DBA algorithms are used. The LR-PON is introduced to cover large scale geographic area in a cost effective way. In the LR-PON, propagation delay is longer due to increase of RTT between the OLT and ONUs. This longer propagation delay is the most threatening part for deploying the LR-PON. The MTP based DBA algorithm is one of the promising solutions to reduce the end-to-end packet delay in the LR-PON system. This MTP based DBA scheme would reduce the overall end-to-end packet delay of the LR-PON compared to the STP based DBA algorithms [3]. The mean packet delay performance of the MTP based DBA algorithms against the STP based DBA algorithms are shown in the [4] for the LR-PON systems. Here, we found that for the LR-PON systems the MTP based DBA algorithms can reduce the end-to-end packet delay. DBA approaches for PONs can be classified according the number of polling threads and three additional main dimensions;

i. The scheduling framework

ii. The sizing the scheduling (along the time axis) of the grants

iii. The upstream transmission windows grants for the individual ONUs

The first MTP based DBA algorithm is introduced in [5] for the LR-PON systems. There are two ways to reduce the end-to-end packet delay in the LR-PON systems;

i. Reduce the DBA execution time. However, in LR-PON, the DBA execution time may not be reduced that much due to the large propagation delay.

ii. Execute the DBA algorithms more frequently. Increased overlapping of EPON DBA processes is achieved by introducing multiple threads running in parallel, which is the concept of the MTP scheme.

3.2.1 Principle of Multi Thread Polling

To achieve better performance in terms of end-to-end packet delay and fairness of bandwidth distribution among the ONUs in a LR-PON, MTP based DBA algorithms are used. Fig. 3.2 shows the exchange of control messages in the MTP based DBA scheme for the LR-PON system [5]. For simplicity, only two ONUs and two threads are shown in the Fig. 3.2. Compared with the STP, shown in Fig. 3.1, there are two “polling processes” or threads running in parallel in the Fig. 3.2 denoted by dark and lighter colors. Let the dark “polling process” be that of the traditional conventional polling scheme for the PON system. Assuming that a packet arrives at ONU_2 at a time as shown in Fig. 3.2, the “Request” message will be sent in the second “polling process” denoted by light color, instead of waiting until the end of data transmission of the first “polling process”. More threads in same time cycle can reduce the end-to-end packet delay effectively.

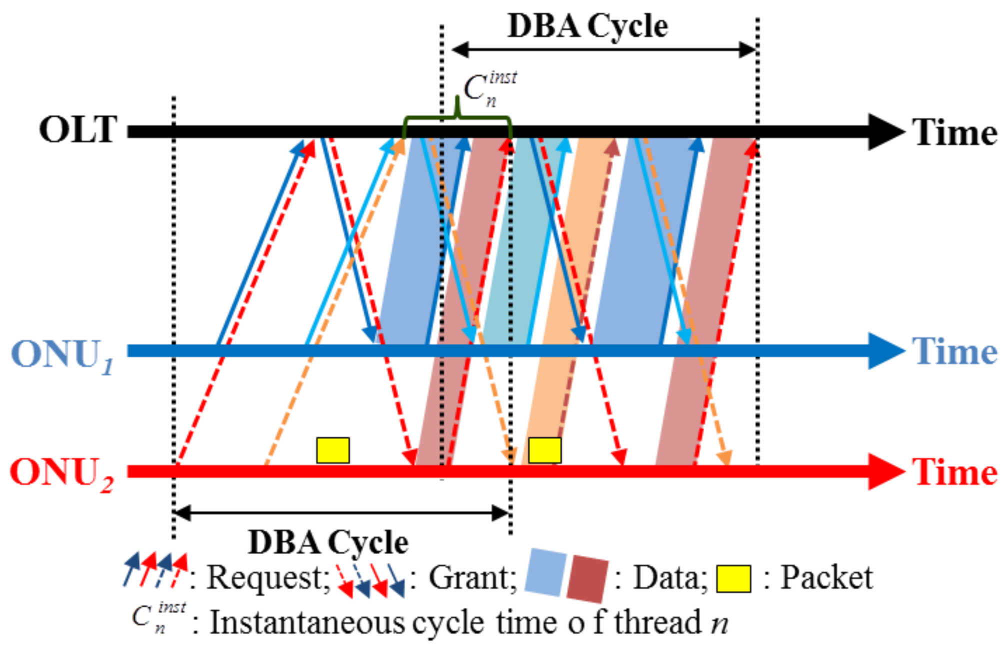


Fig. 3.2 Control messages scheduling diagram in the MTP based DBA scheme [5].

3.2.2 MTP Schemes Grant Allocation Process

To explain the algorithm of MTP scheme we consider two threads, i.e., thread1 (T1) and thread2 (T2), and two ONUs, i.e., ONU_1 and ONU_2 shown in Figs. 3.3, 3.4, 3.5, and 3.6. In the OLT, a polling table for these two ONUs and two threads are used. In the table, each ONU has an entry, which records the ONU’s RTT and its most recent requests in each thread (T1 and T2). Details of the operations are proceedings in [5]. There are five steps of operation for the MTP schemes;

***Step* 1:** Consider time t_0, when the OLT knows how many bytes are waiting in each ONU's buffer from polling table. At time t_0, the OLT sends a Gate message to ONU_1, allowing it to send 5000 bytes as indicated in the polling table.

***Step* 2:** Upon receiving the Gate message from the OLT, ONU_1 starts sending its data up to the size of the granted window, i.e., up to 5000 bytes. During the time interval that ONU_1 waits for the acknowledgement from the OLT, it keeps receiving data from its end user. At the end of transmission window, ONU_1 will generate its own Request, containing the aggregated data size till the Request is generated. This Request is piggybacked to the data transmitted to the OLT. In our example, the new Request is 4500 bytes, as shown in Fig. 3.3.

ONU	T1	T2	RTT
1	5000	4800	500
2	2000	4000	1000

ONU	T1	T2	RTT
1	4500	4800	500
2	2000	4000	1000

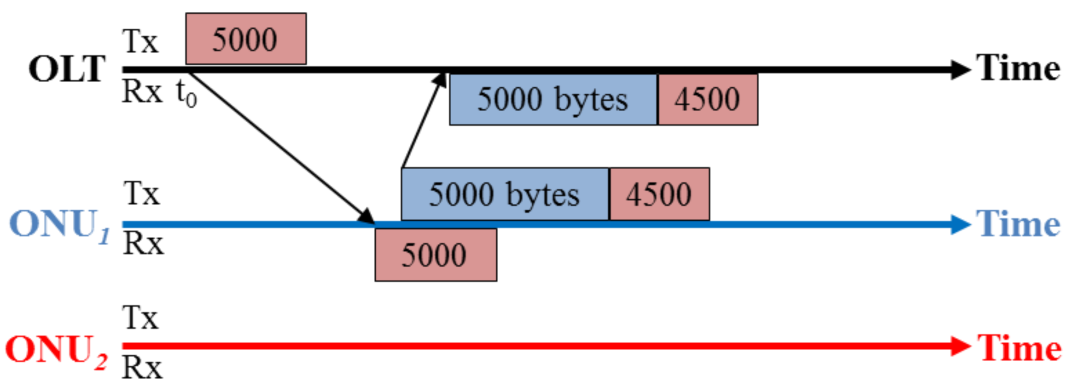


Fig. 3.3 Step 1 and 2 of the MTP based DBA scheme [5].

***Step* 3:** Even before the OLT receives a reply from ONU_1, it knows exactly when the last bit of ONU_1's transmission will arrive. The calculation is simple because the OLT knows the RTT and granted transmission window size for ONU_1. Then, knowing the last bit's arrival time from ONU_1 and the RTT for ONU_2, the OLT can schedule a Gate message to ONU_2 such that the first bit from ONU_2 will arrive with a small guard interval after the last bit from ONU_1. In the example, ONU_2 is granted to send 2000 bytes, as shown in Fig. 3.4.

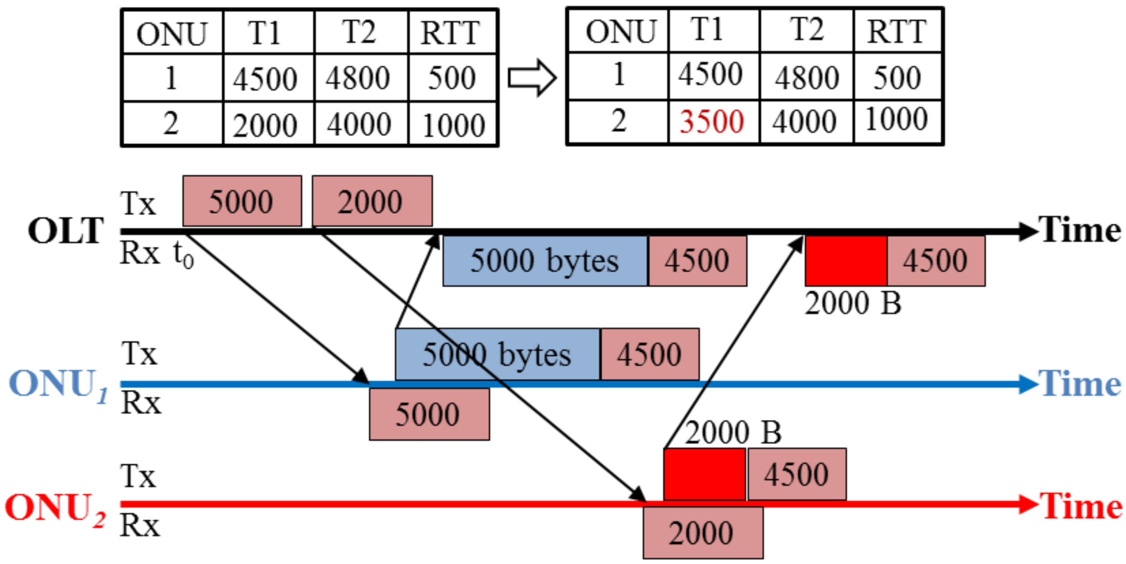


Fig. 3.4 Step 3 of the MTP based DBA scheme [5].

***Step* 4:** Before the new Request from ONU_1 arrives, OLT schedules the Gate message of thread 2 to ONU_1, shown by a green arrow in Fig. 3.5. Similar to Step 3, the OLT can schedule the Gate message to ONU_1 such that the guard interval is maintained between the arrival of the last bit from ONU_2 and the first bit from ONU_1. Here, the OLT allows ONU_1 to send its requested 4800 bytes, which is registered in the polling table as ONU_1's Request of thread $_2$, and this Request was recorded in the previous cycle. Note that, if OLT insists on scheduling the Gate message of thread 1 to ONU_1, the bandwidth cannot be fully used. Even if the OLT sends the Gate message as soon as the new Request of thread 1 from ONU_1 arrives, e.g., 4500 bytes, there is still a wider interval than the guard band between the last bit of the previous ONU_2 transmission and the first bit of ONU_1 transmission.

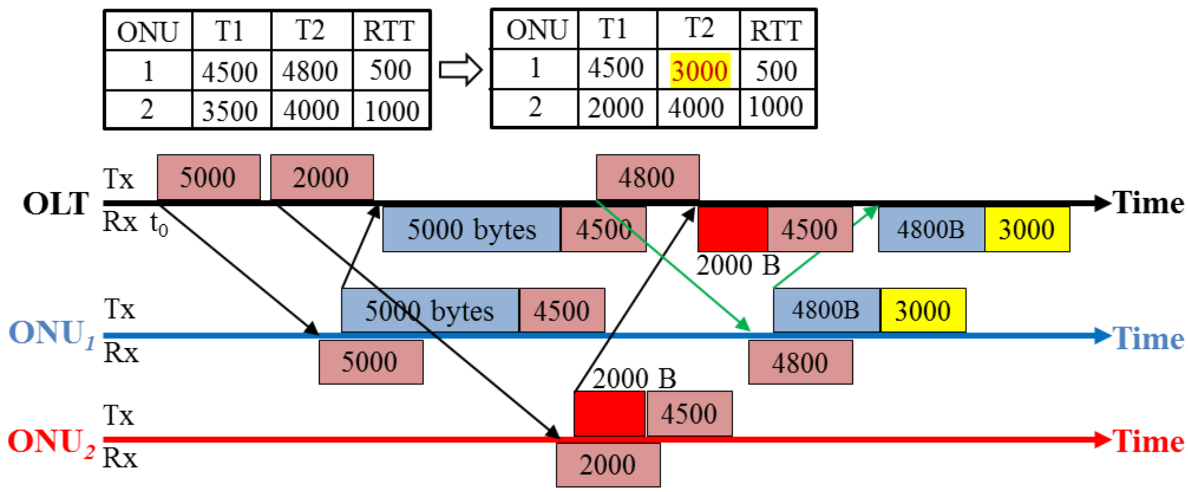


Fig. 3.5 Step 4 of the MTP based DBA scheme [5].

***Step* 5**: Then, OLT schedules Gate message of thread 2 to ONU_2, as shown in Fig. 3.6. Similar calculation as explained in Step 3 applies. The new Gate message allows ONU_2 to transmit its requested 4000 bytes in thread 2. Upon receiving the Gate message, ONU_2 sends 4000 bytes and piggybacks the new Request. When OLT receives the Request of 2500 bytes, it updates the polling table.

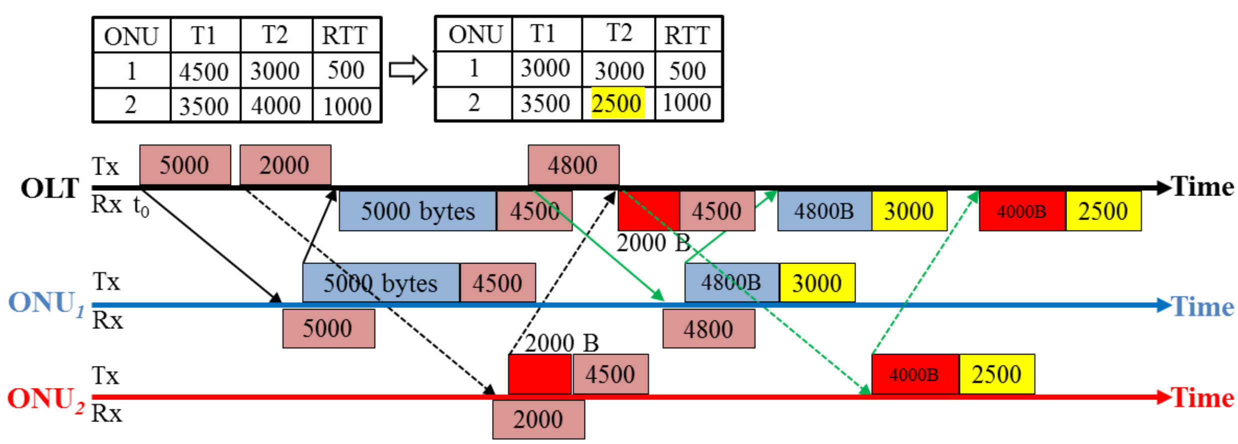


Fig. 3.6 Step 5 of the MTP based DBA scheme [5].

3.2.3 Analysis of Delay for the MTP based DBA Algorithms

The DBA algorithms are depended on the control messages, which are frequently exchanged between the OLT in the CO and ONUs. DBA involves two coexisting processes, determining the granted window size for each ONU and determining the upstream transmission start time of each ONU called grant scheduling. The two processes can be carried out in two ways, by either offline or online scheduling [6]. The offline scheduling scheme is also known as collective scheduling [7]. This scheme enables a globally optimized decision as a result any excess bandwidth from lightly loaded ONUs can be fairly distributed among the heavily loaded ONUs. In online polling, OLT calculate the amount of granted window size just after receiving the Report message and sent to the respective ONU_i.

The LR-PON extends the coverage as well as OLT to ONU from 20 km to 100 km, which increases the RTT from 200 μs to 1 ms [8]. The performance of the conventional STP based DBA schemes are affected by this large propagation delay. The MTP based DBA algorithms can avoid the problem of this large propagation delay. Still the MTP based DBA schemes suffers from three types of delays, i., e., polling delay, grant delay, and queuing delay**.**

Polling delay is the time interval between data packet generated in the queue of an ONU and the transmission of Report message. On average the polling delay is half of the time interval between two successive Report messages of an ONU. Grant delay is the time interval between transmitting a Report message of an ONU and receiving the corresponding Gate message from the OLT. Queuing delay is the delay to transmit the granted window size after receiving the Gate message from the OLT. Instead of these delays, the MTP scheme also suffers from other types of delays. They are processing delay, delay due to guard interval, and idle time between two successive data packets [9].

For using offline MTP based scheduling scheme an idle time of one RTT, which is the time from collecting all reports until the first grant reaches an ONU are induced. This is illustrated in Fig. 3.7. In online scheduling, the DBA decision is made straightaway based solely on the received report. For separating the data packets from overlapping with each other, a small guard band is used between two successive packets in the upstream data transmission. The DBA processing delays in EPON systems are shown in Fig. 3.8. The DBA processing time is very small for the EPON system, i.e., 10 μs [10]. The detail mathematical analysis of the delay for MTP based DBA schemes are given in [11].

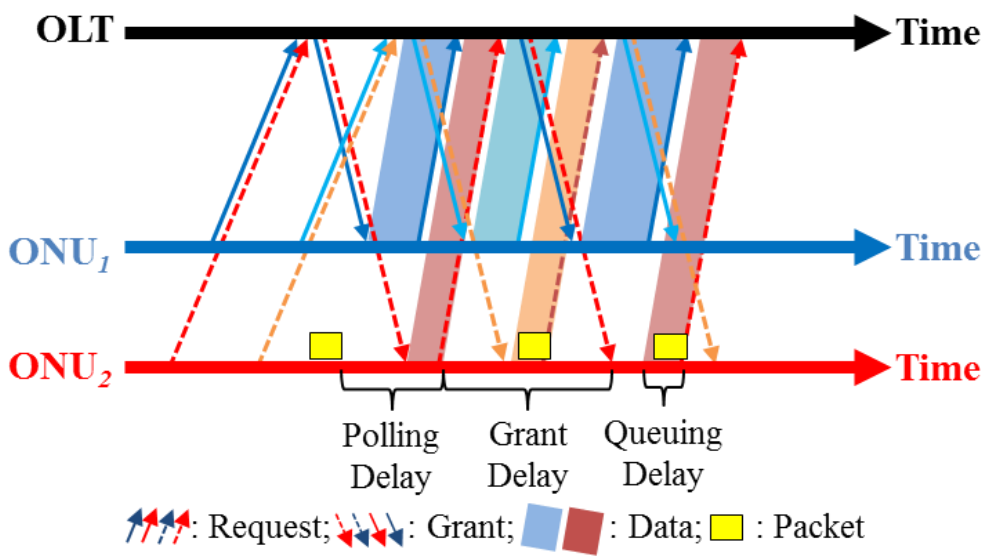


Fig. 3.7 Different delays of the MTP based DBA scheme [9].

3.2.4 Limitations of the MTP Schemes for the LR-PON Systems

Multi-threading or overlapping of DBA processes requires some adjustments to the DBA algorithm. The problem with overlapping DBA processes is that each process by default does not have full information on the impact of other overlapping DBA processes. There is an obvious risk of duplicated traffic reporting in a large degree of over-granting. This problem is accentuated as the DBA process overlapping is increased [12]. Among many existing approaches, the MTP based DBA scheme is considered as one of the most effective options to improve network performance in LR-PONs.

The over-granting problem occurs when the OLT allocates larger window sizes than actually needed by the ONUs. One of the sources of over-granting is related to overlapping of the polling cycles in MTP based DBA schemes. When using multiple threads, the same queued data packets of an ONU may be reported more than once to the OLT.

The MTP scheme for the LR-PON system also introduce some void time between two consecutive data packet transmissions, this void time can increase the overall end-to-end packet delay. As the number of threads or Gate messages are increased, the ONUs are polled more frequently it leads to a large number of Gate and Request messages and thus will waste of bandwidth in control message transmission and guard band overhead. Obviously, if the

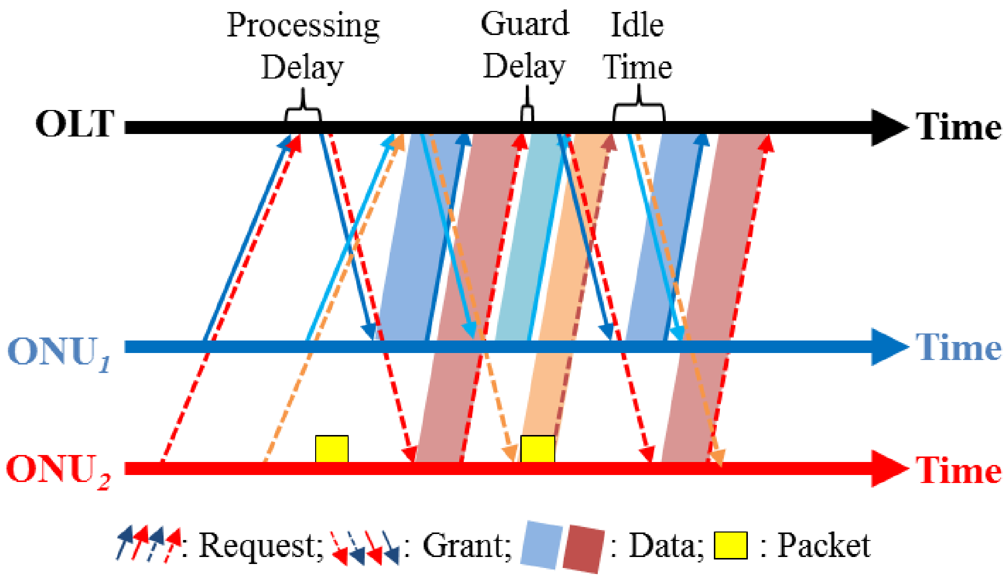


Fig. 3.8 DBA processing delay for the MTP based DBA scheme [9].

traffic load is very high, the bandwidth wastage by the control messages and guard bands will cause more severe problem [13].

There has a large scope of modification and improvement of the QoSs of the existing MTP based DBA schemes. Proper scheduling of the control messages are necessary to reduce the void time and effectively optimize the granting delay for the MTP based DBA scheme. There have some improvement of the MTP based DBA schemes these were proposed in [14 - 21]. However, in the conventional MTP based DBA schemes, over-granting problem is a serious limitation. Most of the MTP based DBA schemes have not considered this over-granting problem. So, to mitigate the over-granting problem in the MTP based DBA schemes for the LR-PON system is a prime goal of this thesis work.

3.3 Survey of MTP Based DBA Algorithms

As stated before, to get the benefit of the LR-PON it requires an efficient MTP based DBA scheme since the conventional STP based DBA schemes lead longer end-to-end packet delays due to larger RTT. The recent research progress shows that advanced DBA scheme is required to overcome the challenges of larger propagation delay in the LR-PON. MTP is one of the promising solutions to reduce the longer propagation delay in the LR-PON. There are already a number of research studies on MTP based DBA scheme that target the DBA performance improvement in the LR-PON. Followings are the major MTP based DBA schemes that improve the performances of the LR-PONs.

3.3.1 Efficient Inter-Thread Scheduling (EIS) DBA

An efficient inter-thread scheduling (EIS) DBA scheme was proposed, they found that without proper inter-communication between the overlapped threads, MTP scheme lost the efficiency and even performed worse than the conventional STP scheme [23]. With this in mind, they designed EIS scheme for LR-PONs. The EIS scheme was designed based on two previously proposed schemes. These schemes are explained in the below;

3.3.1.1 Newly Arrived Plus (NA+) DBA Scheme

In [22, 23], a modified MTP based DBA scheme was described named newly arrived plus (NA+) DBA scheme. The NA+ scheme targeted the over-granting problem, which can be severe in overlapped threads in a typical MTP based DBA scheme. The main idea of the NA+ scheme is that each thread is mainly accountable for the bandwidth allocation for the traffic that has arrived since the initiation of the last DBA process. In this way load is evenly distributed among the different threads. The NA+ scheme can compensate for the backlogged traffic at a specific ONU in the DBA process. A compensation mechanism for backlogged traffic is important because DBA scheme may not be able to cater for all the requested bandwidths in a given DBA cycle. Furthermore, the EPON does not support frame fragmentation and unused time slots may occurs. The NA+ scheme reduced the unused time slots in a DBA cycle. The effectiveness of the NA+ can be clearly observed from Fig. 3.9(a), where an over-granting problem is eliminated by allocating bandwidth only once. For instance, the first arrived packet the blue packet is reported in both $R_{i,1}$ and $R_{i,2}$, but the corresponding bandwidth allocation is only performed once in $G_{i,1}$ because $R'_{i,2}$ excludes the bandwidth of the blue packet, which has already been granted in $G_{i,1}$.

3.3.1.2 Subsequent Requests Plus (SR+) DBA Scheme

Authors of the EIS scheme, called the modified MTP and IPACT scheme as the subsequent requests plus (SR+) DBA scheme. In the SR+ scheme [22, 23], an inter-threading mechanism was introduced that allowed bandwidth allocation even for the packets that arrived at an ONU queue after issuing the report for the current DBA cycle. Therefore, this mechanism to perform bandwidth allocation for subsequent requests can reduce packet delay noticeably in many cases. Fig. 3.9(b) shows the exchanges of control messages for the SR+ scheme employed in a two threaded DBA scheme. Before calculating the bandwidth allocation for the request of $R_{i,1}$, $R_{i,2}$ is also available. So some packets queuing at the ONU_i after the transmission of $R_{i,1}$ have not wait for the reception of $G_{i,2}$ to be transmitted because they have been considered in $R'_{i,1}$ before $G_{i,2}$ is issued and hence could be transmitted as soon as $G_{i,1}$ is received. This clearly reduces the d_{Grant} for the light gray packet shown in Fig. 3.9(b). It should be noted that two packets are reported in $R_{i,2}$, but there is still a risk that not both of them can be transmitted after receiving $G_{i,1}$, because the bandwidth request cannot always be satisfied. Furthermore, the over-granting problem cannot be avoided in the SR+ scheme. For instance, the black packet is considered twice in $R'_{i,1}$.

3.3.1.3 EIS Scheme for the LR-PON

The existing EIS is a hybrid scheme of the NA+ and SR+ schemes to improve the DBA performance in a MTP environment. For bandwidth granting, the EIS scheme considers a newly arrived packet as in NA+ to effectively eliminate the over-granting problem, while bandwidth requested in the subsequent DBA processes is also taken into account as in the SR+ scheme if it arrives before the calculation of the bandwidth granted in the current DBA process. Benefits of employing the EIS can be seen clearly from Fig. 3.10 where d_{Grant} of the packet with the red color can be significantly reduced compared to the NA+ and SR+ schemes. This is because $R'_{i,1}$ can correctly reflect the current bandwidth request. The traffic reported in $R_{i,2}$ can be taken into account when issuing $G_{i,1}$. Furthermore, by eliminating the over-granting for the black packet which has been reported twice, both packets that arrived after $R_{i,1}$ at ONU_i can be transmitted after receiving $G_{i,1}$ [23].

However, due to the DBA control messages in each thread, there is still a linear increase in overhead with respect to the employed number of threads. As both the OLT and ONU are involving in the DBA process, that's why this scheme increased the computational complexity of the overall system.

3.3.2 Enhanced IPACT (E-IPACT) DBA Scheme for the LR-PON

Existing E-IPACT is one of the best schemes that concerns about the over-granting problems in the LR-PON. The E-IPACT scheme states that over-granting problem can be avoided by allowing the ONUs to participate more actively in the DBA process [24]. Any DBA algorithm that utilizes predefined maximum timeslot threshold in the scheduling process is vulnerable to over-granting problem. Any DBA algorithm exploiting a multi-threading strategy for LR-PON is vulnerable to over-granting problem. This problem becomes more evident at high traffic load due to the inefficient upstream channel utilization. There are two root causes of over-granting problem:

i. PON does not support frame fragmentation.

ii. Duplicated reporting in the MTP based DBA algorithms.

In the E-IPACT scheme, the ONU is informed about the maximum window size of a thread $W_{th}^{\max}$ by the OLT using a reserved filed in each Gate message. As a result, the respective ONUs can easily prepare their Report messages that is fitted with the $W_{th}^{\max}$ or integer number of frames. That means in every threads the ONUs receive the information of $W_{th}^{\max}$ from the OLT that helps the ONUs to modify the Report message which is matched with the $W_{th}^{\max}$. That is why, the ONUs must need to actively participate in the DBA algorithm even it is not usual practice in PON system. Fig. 3.11 illustrates the principle of buffer status reporting by an ONU in the existing E-IPACT scheme to avoid the over-granting problem. In this figure, the F_{unR} is the unreported frame of $(j\text{-}1)^{\text{th}}$ time cycle. Similarly, at the time cycle of j the 3$^{\text{rd}}$ Frame *F3* is the unmatched frame which will be treated as F_{unR} of the j^{th} time cycle and it will be reported in the $(j+1)^{\text{th}}$ time cycle.

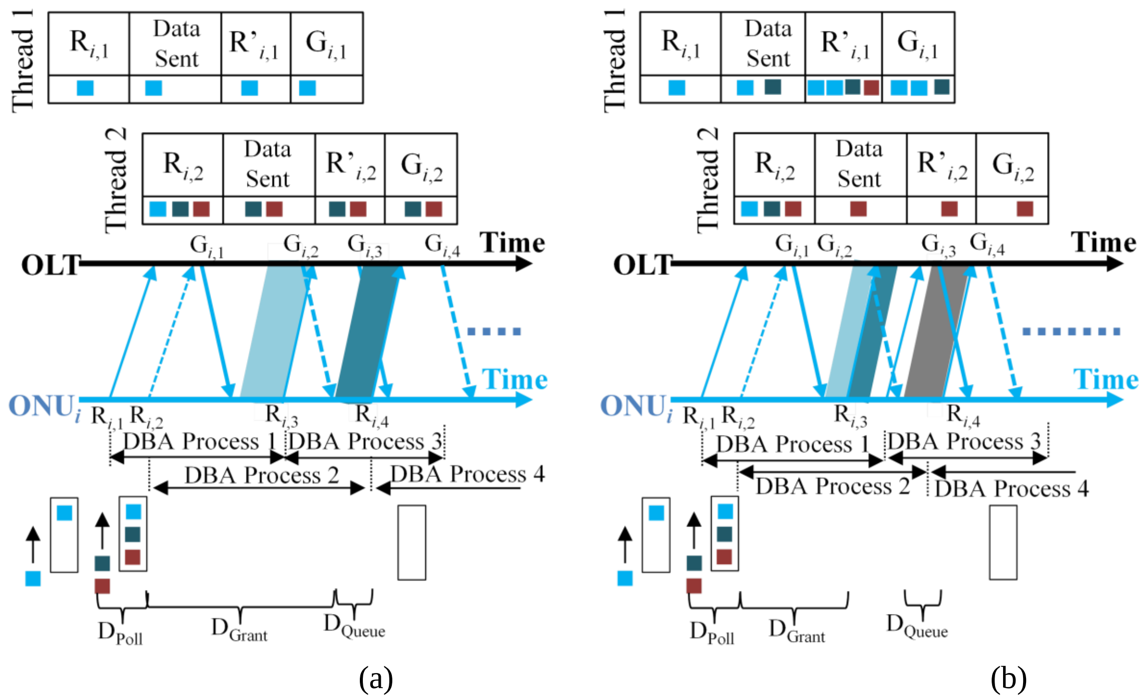


Fig. 3.9 Exchange of control messages for the (a) NA+ scheme, (b) SR+ scheme [23].

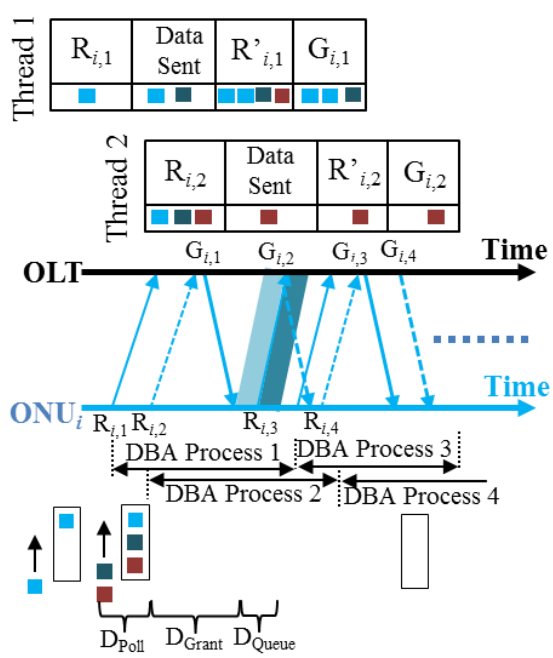
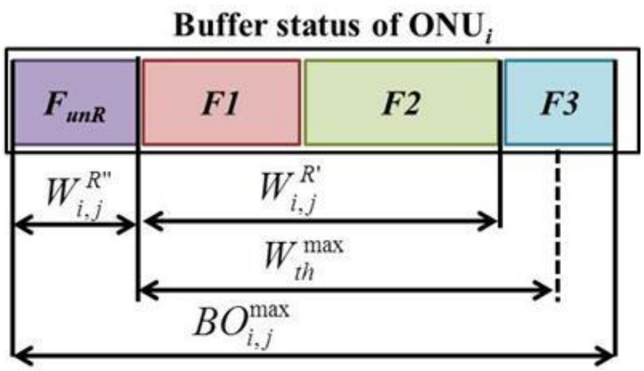


Fig. 3.10 Exchange of control messages for the EIS scheme [23]



F_{unR}: Unreported frame.
$W_{i,j}^{R''}$: Previously reported bandwidth for j^{th} DBA cycle.
$W_{i,j}^{R'}$: The adjusted Report by ONU$_i$ in the j^{th} DBA cycle.
$BO_{i,j}^{max}$: The buffer occupancy at the j^{th} DBA cycle.

Fig. 3.11 Illustration of the buffer status of the E-IPACT scheme [24].

The E-IPACT scheme can reduce the over-granting problem. However, both the control messages, i. e., Report and Gate, require some overheads E_{OH} to schedule the data transmission in the upstream channel. Fig. 3.12 shows the Gate message format in the E-IPACT for the LR-PON system. Here, a Gate message of 64 bytes contains reserved field of 13 to 39 bytes for informing about the W_{th}^{max} to each ONU.

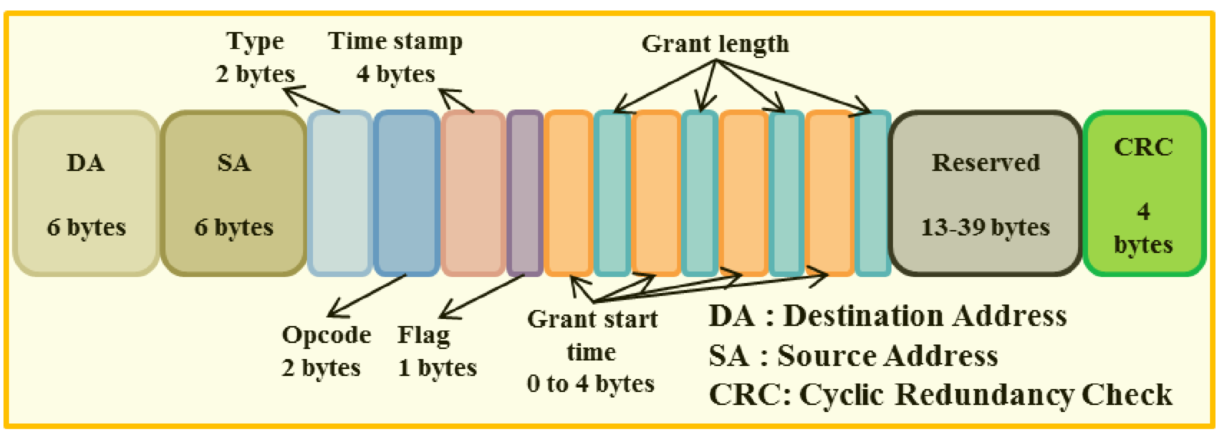


Fig. 3.12 Gate message format for EPON system [25].

The existing E-IPACT scheme suffers from the following complexities:

i. As both the OLT and ONUs are involved in the DBA processing that increase the computational complexity of data packet processing as well as end-to-end packet delay.

ii. In every time cycle, the F_{unR} frames of previous time cycle creates data congestion as well as ONU's buffer overflows in the current time cycle.

iii. The reserved fields in the Gate messages will increase the overheads as well as reduce the bandwidth utilization. This problem will be increased with the number of active ONUs in the LR-PON.

These problem of the E-IPACT and EIS schemes motivates our thesis work to design a new MTP based DBA scheme for the LR-PON system that can mitigate the over-granting problem with lower end-to-end packet delay and computational complexity.

3.4 Chapter Summary

The main purpose of the DBA schemes are to make it sure that there should be no collision in the upstream transmission and also have to ensure QoS issues, which include packet delay, queuing delay, packet loss. In recent research progress several modified MTP based DBA schemes are proposed to improve the performance of the LR-PON system. One of the major problems of the MTP based DBA schemes is over-granting problem. Existing EIS and E-IPACT schemes can reduce the over-granting problem with increasing DBA computational complexity. These schemes motivates this work to design an efficient MTP based DBA schemes to mitigate the over-granting problem with lower end-to-end delay and computational complexity.

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CHAPTER IV

SCHEDULED MULTI GATE POLLING (SMGP) ALGORITHM FOR DELAY REDUCTION OF THE LR-PON

This chapter describes the proposed MTP based DBA scheme for the LR-PON system to reduce the end-to-end packet delay. First of all, the principle of the proposed scheduled multi Gate polling (SMGP) scheme is described in details. Then data scheduling, delay reduction, and fair bandwidth distribution processes are presented sequentially.

4.1 Introduction of Scheduled Multi Gate Polling (SMGP) Scheme

In open access optical network with P2MP structure needs active components to cover large number of users in a wide area. Requirement of more active components increase the network cost significantly. To cover large range congregation of P2MP networks is one of the solutions that reduce the network deployment cost. This idea offers the LR-PON concept having 100 Km spanning of OAN with less number of active components. The LR-PON produces large propagation delay that may appreciably increase the overall transmission delay. To solve this delay problem, in the LR-PON, the MTP based DBA scheme is one of the remarkable solutions [1]. In this thesis, a new MTP based DBA algorithm is proposed for the LR-PON system, named SMGP algorithm. This SMGP algorithm provides new Gate messages scheduling algorithm with proper grant sizing of each ONU that ensures fairness of services and delay diminishing principles.

4.2 Motivations of the SMGP Scheme

There has been growing interest in the study of the advanced bandwidth distribution algorithms for reducing the end-to-end packet delay in the LR-PON based OAN. The interesting point of the PON is that it decreases the cost by reducing the number of active equipment in the network. The rapid growing of PON based OAN induces difficulties to manage large number of users in a long coverage area. The increasing number of users as well as network size also increases the number of network equipment such as splitters, connectors, splices, COs, and access nodes in the conventional short range PONs. Consequently, the overall installation, maintenance and OPEX are also going to high. That is the reason to deploy the LR-PON, where 20 km span of short range PON is enlarged to more than 100 km communication network. The long distance coverage significantly increases the propagation delay as well as end-to-end packet delay. This longer propagation delay is incurred due to larger RTT between the OLT and each ONU. The recent research progress shows that advanced bandwidth distribution schemes is required to overcome the challenges of the larger propagation delay in the LR-PON. It has already said that the MTP scheme is one of the promising solutions to effectively reduce the longer propagation delay in the LR-PON with proper bandwidth utilization. Usually, the bandwidth allocation strategies are classified based on their Report and Gate messages processing approaches. In the existing MTP based DBA schemes, the number of request increases with increasing the number of threads as a result request unbalancing problem is occurred. The IMTP scheme is an improved version of the MTP scheme that solves this request unbalancing problem for the LR-PON [2].

Usually, in the PON system size of data packet of each ONU varies randomly, i.e., traffic pattern is highly bursty. The AMGAV algorithm [3] is proposed to overcome the problems due to bursty traffic of each ONU. Here, the numbers of threads are selected with respect to the offered load of individual ONUs, i.e., number of threads are dynamic not fixed. In [4], MTP algorithm were investigated for systemize inter-communication scheme among the overlapped bandwidth allocation process. They showed that the performance of the MTP based DBA scheme is affected significantly without proper inter-communication bandwidth allocation. Newly arrived plus (NA+) and subsequent request plus (SR+) are two inter thread scheduling schemes presented in [5, 6]. They have investigated the over-granting problem in the conventional MTP based DBA algorithms and proposed a new algorithm called EIS which is the combined version of NA+ and SR+ schemes. In the MTP scheme, threads overlapping are occurred that reduce the performance of the LR-PON drastically. This problem can be solved by thread optimization technique. For requiring of thread optimization, performance of the MTP based DBA scheme is weaker than the conventional STP based DBA algorithms. As the number of threads increases proportionally with the number of request and grant that enhances the over-granting problem. In [7], the over-granting problem is investigated elaborately and they proposed a new algorithm for the LR-PONs called E-IPACT.

In the offline DBA algorithm, the OLT collects the buffer status information from each ONU for bandwidth allocation in the current time cycle. But in the online polling based DBA scheme, buffer status information is not required to grant the window size to an ONU. In [8], online polling based MTP scheme is proposed that reduces the channel idle time as well as average packet delay compared to the offline MTP scheme. In [9], the authors have proposed a new algorithm called adaptive threshold based optical burst assembly in DBA (ATH-DBA) algorithm. This algorithm is the combination of online MTP and adaptive threshold based optical burst assembles. All the above online MTP based schemes suffer from proper management of multiple Reports and Gates scheduling. The overall performance of the online MTP based DBA scheme of the PON system can be improved by ensuring proper management of these Report and Gate messages in a time cycle.

In this thesis, the MTP based SMGP scheme is proposed to optimize the number of threads in a time cycle and reduce the overall packet delay. In addition to the thread optimization, the SMGP scheme provides proper management of the Report and Gate messages scheduling to ensure the fair bandwidth distribution among the ONUs and avoid the over-granting problem. In the proposed SMGP scheme, the maximum cycle length $T_{cycle}^{\max}$ is subdivided into multiple small processing time T_{GS} units. In a T_{GS} unit, the Gate messages must be sent in response to the respective Report messages just at the end of this T_{GS} unit. Here, the Gate messages in each T_{GS} unit are scheduled properly for avoiding void time between two successive data transmissions. For fair bandwidth distribution among the ONUs a grant utilization factor is also used. This grant utilization factor reduces the reporting delay as well as granting delay for each thread.

4.3 Principle of the Proposed SMGP Scheme

One of the major problems of the MTP based DBA schemes are indicated in IMTP scheme that is request unbalancing problem. According to the EIS scheme, without proper management of the control messages, i.e., Report and Gate messages, the performance of the MTP based DBA schemes for the LR-PON is gone down even compared to the STP or conventional polling schemes. The MTP based DBA scheme provides data transmission scheduling with shorter idle times. Each ONU can send more than one consecutive Report messages to the OLT in a single time cycle. In a time cycle, the number of threads is defined by the number of Report messages send by an ONU. More threads in the same time cycle can reduce the reporting and queuing delays effectively. Still the grant delay is equal to or greater than the RTT of the ONUs. However, the complexity of a DBA algorithm is dependent on the number of threads. In the MTP based DBA algorithm, the granted window size for a Report message depends on the number of threads and maximum length of a time cycle, $T_{cycle}^{\max}$. Following equation is used to calculate the maximum window size $W_i^{\max}$ of an ONU *i* [10].

$$W_i^{\max} = \frac{T_{cycle}^{\max} - T_G \times (N-1)}{N} \tag{4.1}$$

where, T_G is the guard interval and *N* is the total number of ONUs in the LR-PON.

For *n* number of threads the maximum window size $W_{th}^{\max}$ of each thread of an ONU is calculated by using the following formula [10];

$$W_{th}^{\max} = \frac{W^{\max}}{n} \tag{4.2}$$

here, the number of thread *n* can be less than or equal to the number of services connected to an ONU.

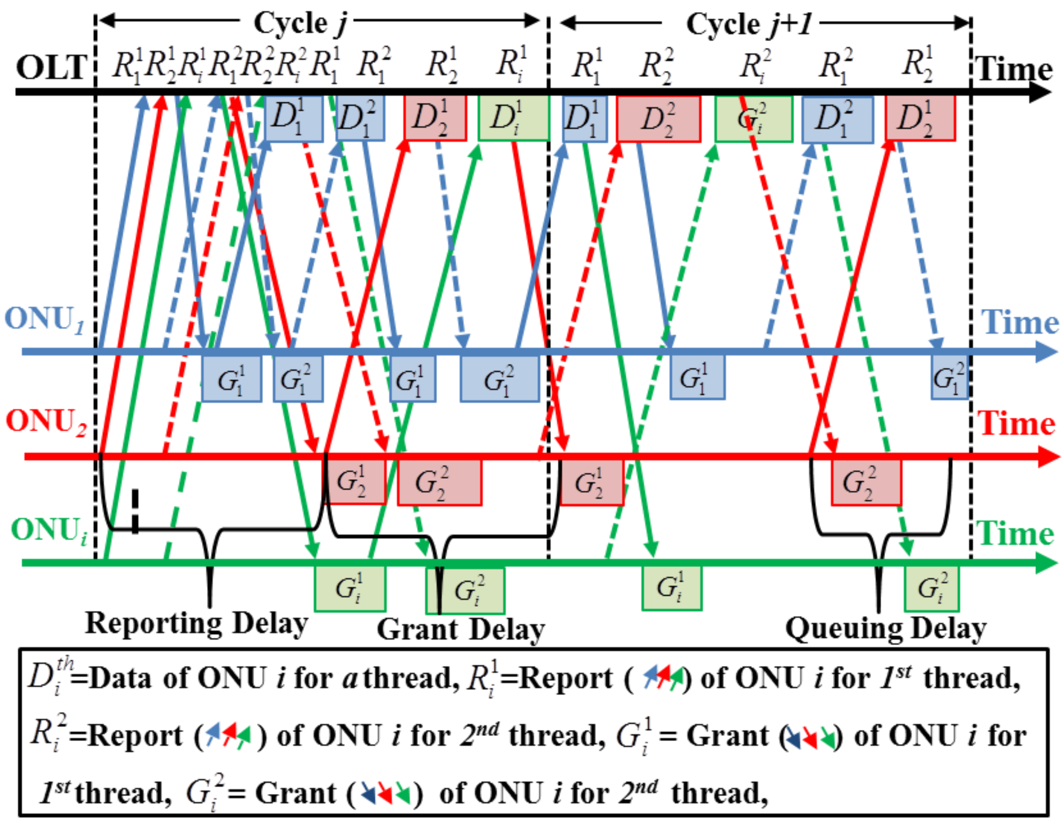

Fig. 4.1 Exchange of control messages in the existing MTP based DBA schemes.

Fig. 4.1 shows the exchange of control messages in the MTP based DBA schemes, where *i* number of ONUs sent their data packet in upstream direction using two threads. But when the number of threads is increased it makes the scheme complicated for distributing the upstream bandwidth to each of the ONU. The MTP based DBA scheme also creates larger void time between two successive data transmissions and data overlapping that's lost the upstream data packets. However, sophisticated control message scheduling schemes is required to mitigate these problems.

4.3.1 Primitive Idea of the SMGP Scheme

In the proposed SMGP scheme, the total upstream cycle time T_{cycle} is divided into several grants processing time T_{GS} units. The two subsequent T_{GS} units are separated by a guard interval. Similar to the conventional online polling scheme, the entire ONUs can send their request messages together at any time or before getting the previous Gate messages sent by the OLT. After just finishing of the k^{th} processing time T_{Proc}^{k} unit, the OLT sends all the corresponding Gate messages together to the respective ONUs. If any Report is arrived on the guard time, that Report is processed on the next, i.e., $(k+1)^{th}$, processing time T_{Proc}^{k+1} unit.

In the next stage, the excess bandwidths from the lightly loaded ONUs are distributed on fair-demand basis of the heavily loaded ONUs. That means, there must be a transparency of granting window sizes among the heavily loaded and lightly loaded ONUs of the PON system. This justification of transparency is performed by a utilization factor, U_F. The U_F can change the granted window sizes according to the request of all the ONUs.

Benefits of the SMGP scheme can be explained in two different cases,

- The over-granting problem of the conventional MTP based DBA scheme is avoided by using this T_{proc}. The proposed SMGP scheme significantly reduces the void time between two successive data transmissions with rapid Gate distribution among the ONUs.
- The U_F plays a vital role to distribute the excess bandwidth from the lightly loaded ONUs to the heavily loaded ONUs. Because the requested window size of an ONU is not fixed it varies not only based on its demand but also requested window sizes of other ONUs. This effect is more significant for heavily loaded ONUs.

4.3.2 Principle of Bandwidth Allocation in the Proposed SMGP Scheme

In the SMGP scheme, reduction of the end-to-end delay in the LR-PON is achieved in two ways, i.e., reduction of polling delay by elimination of idle time and reduction of granting delay. The maximum cycle time T_{cycle}^{max} in a time cycle is subdivided into different small grants scheduling T_{GS} units. We also proposed to use a small guard band T_{Gb}^{Gate} between two consecutive T_{GS} units to separate them. In every T_{GS} unit of a time cycle, the OLT waits and receives multiple Report messages from different ONUs and then prepares and sends respective Gate messages. For example, if *r* number of Report messages is reached in a T_{GS} unit, then the *r* Gate messages will be sent to the respective ONUs at the end of that T_{GS} unit. Each T_{GS} unit is notified about the current scheduling status of a time cycle from the previous T_{GS} unit of that time cycle. Moreover, any report reaches in the T_{Gb}^{Gate} will be process in the next T_{GS} unit.

Fig. 4.2 shows Report messages scheduling diagram in the OLT of the proposed SMGP scheme. Here, we consider a time cycle *j* with maximum length $T_{cycle}^{\max}$ which is subdivided into 6 different T_{GS}^{j} units and two consecutive T_{GS}^{j} units are separated by a T_{Gb}^{Gate}. The schedule time slot $T_{Sc}^{i,th}$ is the time period reserve for the upstream data packets of a thread of an ONU *i*. Following features can be found from the Fig. 4.2:

- At the end of a time cycle, if there is any F_{unR} then no need to send further Report message for this F_{unR} in the 1st T_{GS} unit of the next time cycle. Because the Gate message automatically incorporates that F_{unR} in the next time cycle. In this way, the proposed scheme1 effectively eliminate the possibility of duplicate Report message transmission.
- As T_{Sc}^{th} is strictly maintain in the every thread of an ONU for each time cycle there is no possibility of idle time in the upstream time frame of the LR-PON.
- In the proposed scheme1, both the granting and polling delays are reduced by transmitting multiple numbers of Gate messages together to different ONUs at the end of each T_{GS}^{j} unit.

The relation between $T_{cycle}^{\max}$ and T_{GS}^{j} units can be obtained by the following equation,

$$\alpha = \frac{T_{cycle}^{\max}}{T_{GS} + T_{Gb}} \tag{4.3}$$

where, α is the total number of T_{GS} units in a time cycle.

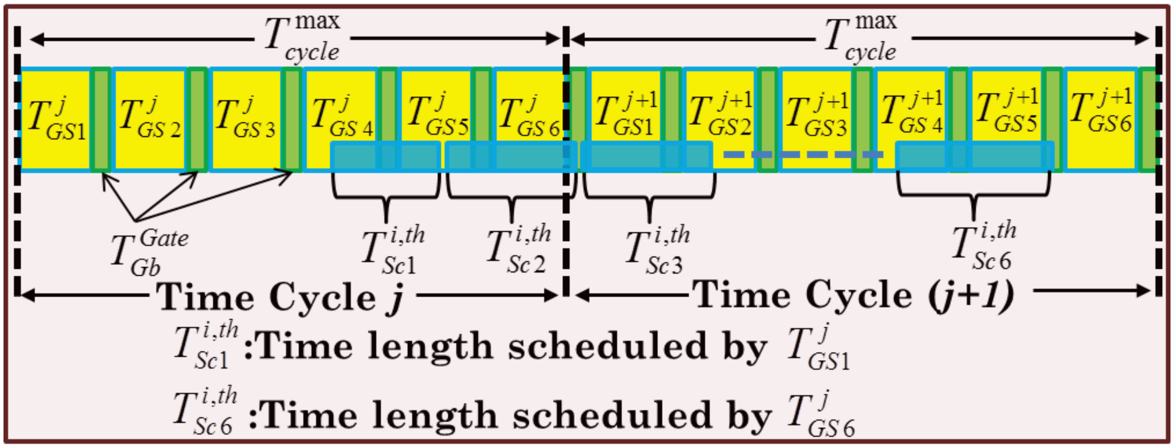

Fig. 4.2 Report scheduling diagram in the OLT of the SMGP scheme.

Fig. 4.3 represents the principle of control messages scheduling for the proposed scheme in two time cycles of *j* and *j*+1. For simplicity, in the figure, we have considered an LR-PON system with two ONUs and two threads for each ONU. Here, data packets of thread1 of ONUs 1 and 2, i.e., $D_{1,1}$ and $D_{1,2}$, respectively, are reached to the OLT during the T_{GS2}^{j} unit. So, at the end of the T_{GS2}^{j} unit the respective Gate messages of thread2 of ONUs 1 and 2, i.e., $W_{2,1}^{G}$ and $W_{2,2}^{G}$, respectively, are sent to those ONUs at the same time. From this control messages scheduling algorithm it is clear that the granting and polling delays will be reduced because of the Gate messages of multiple threads of different ONUs are sent without any time interval.

4.3.3 Fair Bandwidth Utilization Process in the SMGP Scheme

In a specific time cycle, the number of the T_{proc} is fixed. The following equation is used to calculate the number of total T_{proc} in a time cycle;

$$\text{No. of } T_{proc} = \frac{T_{cycle}^{\max}}{L_{proc}} \tag{4.4}$$

where, $T_{cycle}^{\max}$ is the maximum length of a time cycle and L_{proc} is the length of a T_{proc}.

For the lightly loaded ONUs the U_F is unity while Eq. 4.5 is used to calculate the U_F for the heavily loaded ONUs.

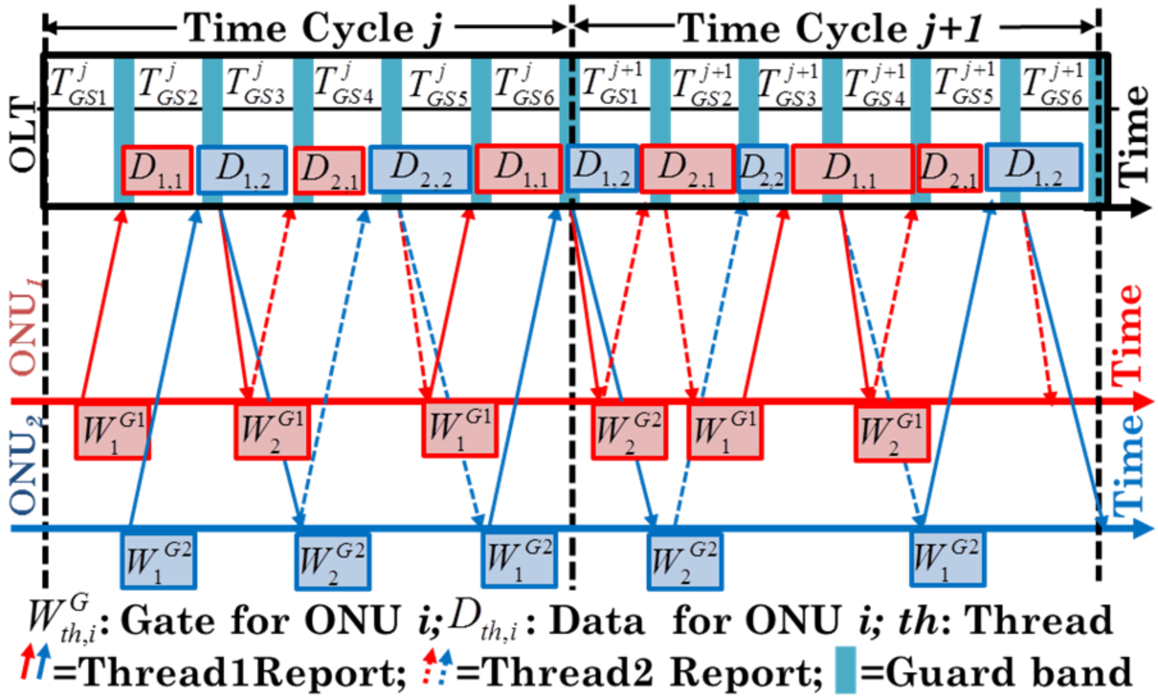

Fig. 4.3 Control messages scheduling diagram for the proposed SMGP scheme.

$$U_F = \frac{\sum_{i=1}^{N} R_i^n}{T_{Cycle}} \tag{4.5}$$

Alike the conventional MTP based DBA schemes, in the proposed scheme, the excess bandwidth is also calculated from the lightly loaded ONUs. Following formula is used to calculate this excess bandwidth Ex_i^{th} of a thread of an ONU i [10];

$$Ex_i^{th} = \begin{cases} 0 & \text{for } W_{th}^R > W_{th}^{\max} \\ (W_{th}^{\max} - W_{th}^R) & \text{for } W_{th}^R \leq W_{th}^{\max} \end{cases} \tag{4.6}$$

Total excess bandwidth Ex_T^{th} of a thread of all the lightly loaded ONUs in a time cycle is:

$$Ex_T^{th} = \sum_{i=1}^{L_N} Ex_i^{th} \tag{4.7}$$

here, L_N indicates the total number of lightly loaded ONUs in the network in a time cycle.

This Ex_T^{th} is equally distributed to the heavily loaded ONUs. So the excess bandwidth W_{Ex}^{th} for each heavily loaded ONU in a thread is for H_N number of heavily loaded ONUs

$$W_{Ex}^{th} = \frac{Ex_T^{th}}{H_N} \tag{4.8}$$

In addition to the excess bandwidth allocation to the heavily loaded ONUs, we also proposed to redistribute the granted window sizes for all the ONUs by using U_F. The U_F ensures fair-demand based grant scheduling among all the ONUs in the LR-PON system. Bandwidth allocation in a thread among both the lightly and heavily loaded ONUs based on the proposed SMGP scheme is presented in Eq. 4.9.

$$W_{th}^{G} = \begin{cases} W_{th}^{R} & \text{if } W_{th}^{R} < W_{th}^{\max} \\ \dfrac{W_{th}^{R}}{U_F} & \text{if } W_{th}^{\max} \le W_{th}^{R} \le (W_{th}^{\max} + W_{Ex}^{th}) \\ \dfrac{W_{th}^{R}}{U_F} + W_{Ex}^{th} & \text{if } W_{th}^{R} > (W_{th}^{\max} + W_{Ex}^{th}) \end{cases} \tag{4.9}$$

Now the total allocated bandwidth W_i^T to an ONU *i* for all the threads in a time cycle is calculated using the Eq. 4.10.

$$W_i^T = \sum_{th=1}^{n} W_{th}^{G} \tag{4.10}$$

Due to consideration of the U_F, in the proposed scheme, the bandwidth is allocated to all the ONUs fairly that reduces the grant delay effectively. The T_{proc} is a unique parameter used in the proposed DBA scheme it helps to distribute the Gate messages to the ONUs rapidly that reduces the reporting delay.

4.4 Chapter Summary

In this thesis work, a new MTP based DBA scheme called SMGP scheme is proposed for the LR-PON based access network. Due to the consideration of U_F the proposed SMGP scheme resolves the bandwidth allocation discrepancy between the lightly loaded and heavily loaded ONUs. This SMGP scheme provides new Gate messages scheduling with proper grant sizing of each ONU that provides fairness of services and reduces the end-to-end packet delay significantly compared to the existing MTP based DBA schemes.

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CHAPTER V

DBA ALGORITHM FOR SOLVING THE OVER-GRANTING PROBLEM OF THE LR-PON

This chapter describes the methodology of the proposed Scheme2 for mitigating the over-granting problem as well as increasing the bandwidth utilization of the LR-PON system with lower computational complexity. Firstly, the induced process of over-granting problem in the MTP based DBA schemes are described in detail. The methodology of the existing E-IPACT scheme to reduce the over-granting problem and limitation of this scheme is described in Section 5.3.2. Finally, the over-granting elimination process, control message scheduling, ONU's buffer modeling, grant allocation process, and computational complexity analysis of the proposed scheme2 are depicted in details.

5.1 Introduction of New DBA Scheme for Solving the Over-Granting Problem

The LR-PON system requires larger propagation delay as well as end-to-end packet delay. These delays significantly degrade the performances of the existing centralized DBA algorithms of the LR-PON. That is why advanced DBA schemes are required to reduce the longer propagation as well as end-to-end delays in the LR-PON. Proper scheduling of the Report and Gate messages is one of the main challenges to design a sophisticated DBA algorithm for the LR-PON. Without proper management of the Report and Gate messages, the LR-PON system suffers from over-granting problem. In this thesis work totally two DBA schemes were proposed, i.e., Scheme1 (SMGP) and Scheme2, for the LR-PON system. The Scheme1 is used to reduce the end-to-end packet delay described in Chapter 4 while the Scheme2 is used to mitigate the over-granting problem. In the Scheme2, each of the ONU will send the frame information instead of total buffer occupancy to avoid the over-granting problem. The combined effect of the Scheme1 called SMGP and Scheme2 effectively improves the overall QoSs of the LR-PON system.

5.2 Motivations of the DBA Scheme2 for Solving the Over-Granting Problem

In the MTP scheme, multiple threads are running in parallel that reduces the polling and queuing delays significantly [1]. The main problem of an MTP scheme is that the current DBA process does not carry the information of the previous DBA process. As a result, there is a chance to Report the same data packets twice in one-time cycle. With increasing the number of threads, the chance of this duplicated Report message is also increased [2]. Moreover, the EPON system does not allow any frame fragmentation. As a result, if the requested window size from an ONU does not match with the maximum granted window size, then the DBA schemes suffers from the over granting problem. Most of the MTP based DBA schemes are inherently suffered from the over-granting problem. The over-granting problem occurs when the DBA algorithm allocates a larger timeslot size than actually needed by the ONU [3].

To solve the over-granting problem in the LR-PON, the EIS algorithm is proposed [4]. The EIS scheme ensures the better inter-thread communication in the case of overlapped DBA cycle. The E-IPACT is another promising algorithm proposed for solving the over-granting problem. Both the EIS and E-IPACT schemes successfully eliminate the over-granting problem by matching the requested window size with the integer number of frames. But these two schemes require more computation time as both the ONU and OLT perform the DBA process. Due to the over-granting problem, all the existing MTP based DBA schemes suffer from duplicate Report message transmission, unused or wastage of timeslot, and timeslot overlapping. These problems degrade the overall performances, e.g., frame loss, bandwidth utilization, and jitter etc., of the LR-PON.

Two new MTP based DBA algorithms, i.e., Scheme1 (SMGP) and Scheme2, for the LR-PON are introduced that eliminate the over-granting problem with lower computational complexity and lower end to end packet delay. In this Scheme2, the DBA algorithm is performed only by the OLT instead of both the OLT and ONUs. Alike the existing E-IPACT the OLT does not need to transmit the maximum granted window size $W_{th}^{\max}$ in each thread. That is why the ONUs does not need to participate in the DBA process. To avoid the frame fragmentation as well as over-granting problems, each ONU sends the Report message containing the required frame information and the OLT match it with the $W_{th}^{\max}$ to calculate the number of granted frames. Combination of these two proposed schemes effectively mitigate the limitations of the existing MTP based DBA algorithms and improve the overall QoSs of the LR-PON system.

5.3 Existing Schemes: Over-Granting Effects in the LR-PON

In the following sections, at first we explain the conventional control message scheduling principle for the MTP based DBA schemes in the LR-PON system. Then, we explain the principle of the existing E-IPACT scheme with its limitations.

5.3.1 Control Message Scheduling for the MTP based DBA Schemes of the LR-PON

The process of control messages scheduling and data packet transmission of the MTP based DBA scheme for the LR-PON system is shown in Fig. 5.1. Here, for simplicity, we have considered two ONUs and two different threads for each ONU. However, the number of ONUs and threads can be varied. The maximum buffer size $B_{th}^{\max}$ of a thread of an ONU depends on the summation of the maximum values of three frames. We also considered that the maximum granted window size $W_{th}^{\max}$ of a thread is not more than 3000 bytes. From the Fig. 5.1, we can see that the requested window size W_{th}^{R} for the thread1 of both the ONU_1 and ONU_2 are 2400 and 3100 bytes, respectively. In the response, the granted window size W_{th}^{G} is 2400 bytes for the thread1 of ONU_1 as the W_{th}^{R} is less than the $W_{th}^{\max}$. In contrast, for thread1 of ONU_2, the maximum W_{th}^{G} is 3000 bytes as the W_{th}^{R} is greater than the $W_{th}^{\max}$. However, the transmitted window size Dp_{th}^{sent} for thread1 of ONU_2 is 1600 bytes. Because the EPON system does not allow any frame fragmentation. Here, the W_{th}^{G} didn't match with the summation of the three frame sizes. So instead of fragmentation of 3rd frame, the ONU_2 only transmits the first two frames $F(1100, 500)$ to the OLT and 3rd frame is remained as unreported frame F_{unR} of the thread1 of the ONU_2. In this way, the MTP based DBA schemes suffer from the over-granting problem because the W_{th}^{G} is larger than the actual Dp_{th}^{sent}.

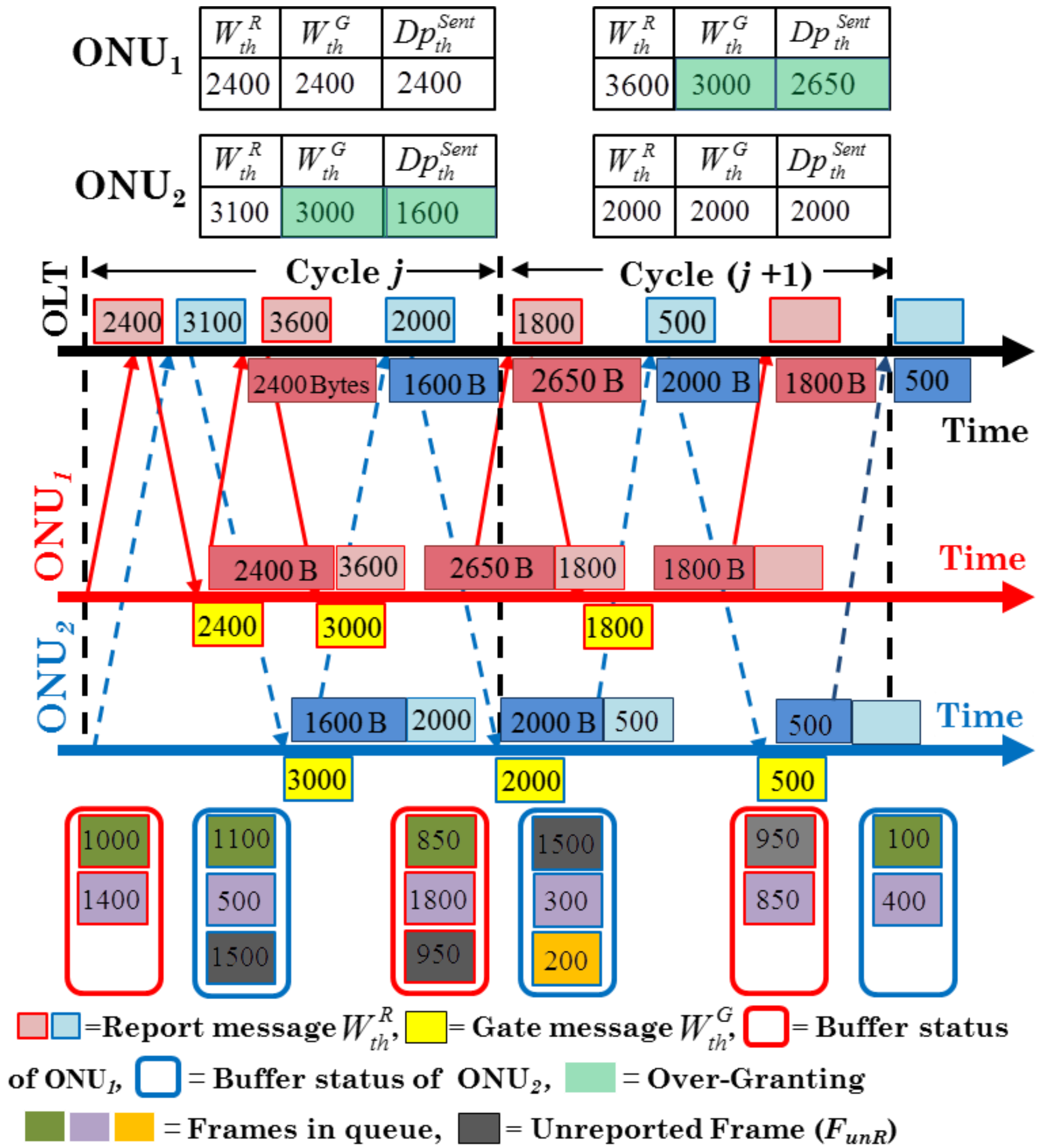

Fig. 5.1 Control message scheduling and introducing over-granting problem in the MTP based DBA algorithms for the LR-PON.

The F_{unR} of the thread1 of ONU$_2$ will be added with the W_{th}^{R} of thread2 of the ONU$_2$ in the same time cycle. As a result, the same frame is requested twice and this increases the overhead E_{OH} in the existing MTP based DBA schemes.

The major shortcomings of the existing MTP based DBA schemes are as follows:

- As the over-granting problem is existed, the bandwidth is being wasted and creates lower bandwidth utilization (BWU).
- The LR-PON systems also suffer from longer end-to-end delay due to the bandwidth wastage.
- There is no coordination between two successive time cycles and if there is any F_{unR} between these two time cycles then it may be lost.

5.3.2 Existing E-IPACT Scheme and its Limitations for the LR-PON System

The existing E-IPACT scheme states that the over-granting problem can be avoided by allowing the ONUs to participate more actively in the DBA process. However, in the general case of PON technology, only the OLT is responsible to participate in the DBA process. In the E-IPACT scheme, the ONU is informed about the $W_{th}^{\max}$ by the OLT using a reserved filed in each Gate message. As a result, the respective ONUs can easily prepare their Report messages that is fitted with the $W_{th}^{\max}$ or integer number of frames. That means, in every threads, the W_{th}^{R} sent by any ONU to the OLT is previously modified to make it matched with the $W_{th}^{\max}$. That is why, the ONUs must need to actively participate in the DBA algorithm even it is not usual practice in the PON systems [3, 4].

The E-IPACT scheme can successfully reduce the over-granting problem in the existing MTP based DBA algorithms. However, the control messages, i. e., Report and Gate, require some overheads to schedule the data transmission in the upstream channel.

The existing E-IPACT scheme suffers from the following complexities:

- As both the OLT and ONUs are involved in the DBA processing that increases the computational complexity of data packet processing as well as end-to-end packet delay.
- In every time cycle, the F_{unR} of the previous time cycle creates data congestion as well as ONU's buffer overflow in the current time cycle.

The reserved fields in the Gate messages will increase the overheads as well as reduce the BWU. This problem will be increased with the number of active ONUs in the LR-PON system.

5.4 Elimination of the Over-Granting Problem with Lower Computational Complexity

The main objective of the scheme2 is the elimination of the over-granting problem and reduction of the computational complexity of the MTP based DBA algorithms in the LR-PON system. The scheme2 has following three features that ensure the improvement of QoSs of the LR-PON system:

i. In the proposed scheme2, the ONUs sends the required frames information in the Report message. However, in the conventional DBA algorithms, the ONUs sends the total buffer information in the Report message. This technique helps to mitigate the over-granting problem in the LR-PON system.

ii. No need to send the information of the size of $W_{th}^{\max}$ in the every Gate messages, which reduces the E_{OH} and increases the BWU in the LR-PON.

iii. Unlike the E-IPACT, in the proposed Scheme2, only the OLT performs the DBA calculation that reduces the computational complexity.

5.4.1 ONU's Buffer Modeling

Since the Report messages of the ONUs consist of buffer information frame by frame, the total buffer status of a thread of an ONU i at a time cycle j can be obtained by the following equations,

$$B_{i,j}^{th} = \sum_{l=1}^{k} F_i^{l} \tag{5.1}$$

$$F_{unR}^{th} = \sum_{w=0}^{s} F_i^{k-w} \tag{5.2}$$

here, F_i^l is the size of frame l of the i^{th} ONU, k is the maximum number of frames in a thread and F_{unR}^{th} is the summation of unreported frames in a thread.

To make a Report message for a thread of an ONU, it is essential to maintain and upgrade the buffer status of each ONU properly. In the case of MTP based DBA scheme, this process should be more sophisticated to obtain the optimum performance of the LR-PON system. At the time cycle j the W_{th}^R for a thread can be obtained by the following equation;

$$W_{th}^R = B_{i,j}^{th} + F_{unR}^{th-1} \tag{5.3}$$

Therefore, in a thread, the W_{th}^R of a Report message of an ONU depends on the current buffer status and summation of previous unreported frames, i.e., F_{unR}^{th-1}, of that ONU.

5.4.2 Grant Allocation Process of the Proposed Scheme2

Fig. 5.2 shows the principle of grant allocation in the proposed scheme2. Here, the W_{th}^R contains the information of frame sizes sequentially, i.e., F_i^1, F_i^2, … F_i^k. In a time cycle, the $W_{th}^{\max}$ is fixed and it is set by the following equation (similar like Eq. 4.1);

$$W_{th}^{\max} = \frac{T_{cycle}^{\max} - (i-1) \times T_{Gd}}{i \times n} \tag{5.4}$$

The benefit of the proposed scheme2 is that, the ONUs do not need to perform DBA processing. As soon receiving the W_{th}^R the OLT calculates the number of granted frames that matched with the $W_{th}^{\max}$. To avoid the frame fragmentation the W_{th}^G must be the summation of integer number of frames that is upper bounded by the $W_{th}^{\max}$.

For simplicity, in the Fig. 5.2, we have considered maximum two ONUs and two threads per ONU in each time cycle. We also have considered that the buffer size is up to three frames in each thread of an ONU. The grant allocation process of the OLT in the Scheme2 can be explained by the following steps

First. Considering no F_{unR} at the thread1. The buffer of the j^{th} time cycle of thread1 of ONU1 contains two frames, i.e., F_1^1 and F_1^2, thus $W_{th1}^{R,j} = F_1^1 + F_1^2$ which

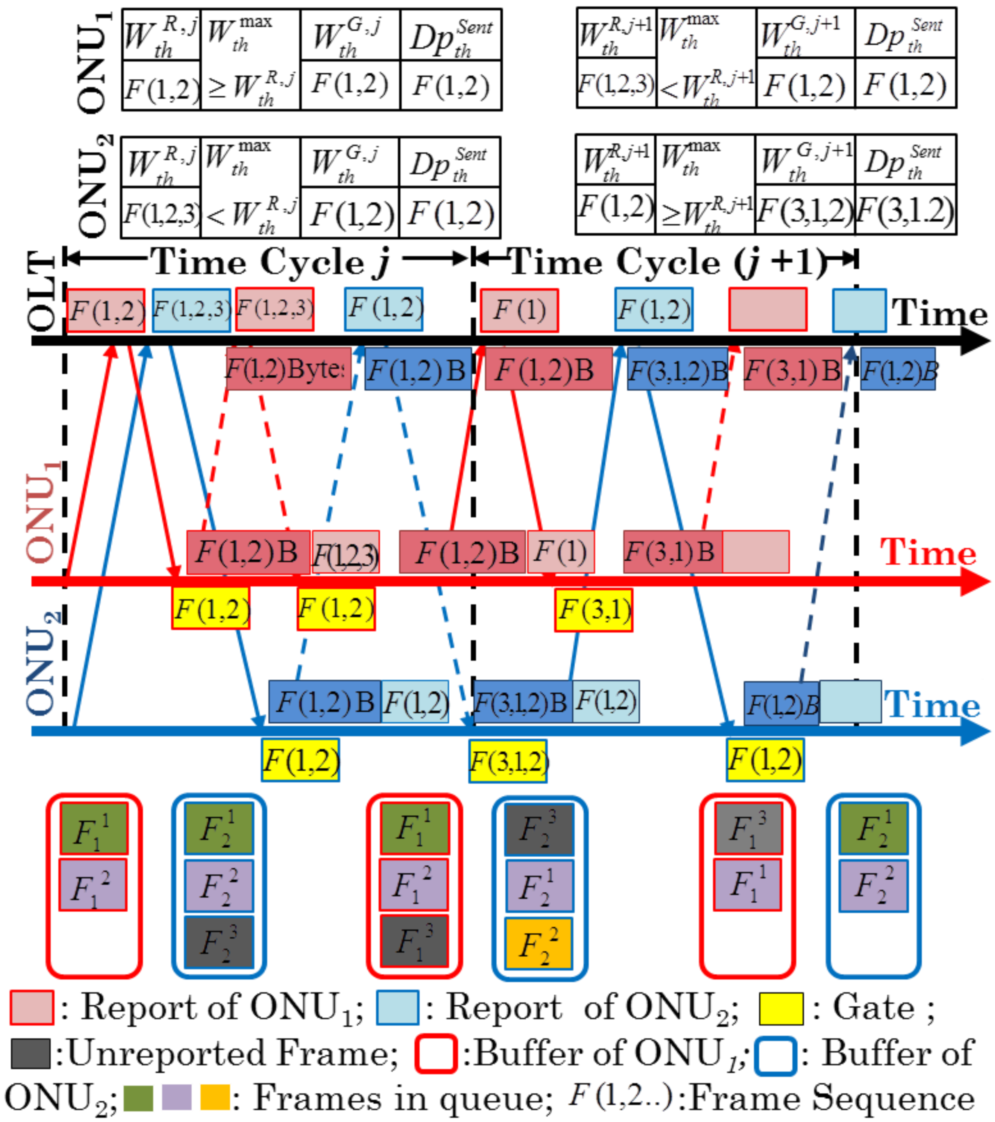

Fig. 5.2 Principle of grant allocation process in the proposed scheme2.

is assumed to be less than $W_{th}^{\max}$. Therefore, the $W_{th1}^{G,j}$ of ONU*1* is same as the $W_{th1}^{R,j}$ and that can be achieved by the following formula;

$$W_{th1}^{G,j} = W_{th1}^{R,j} = \sum_{l=1}^{k} F_1^l \qquad \text{if } W_{th1}^{R,j} \le W_{th}^{\max} \tag{5.4}$$

Second. In the thread2 of ONU$_1$, the buffer has three frames, i.e., F_1^1, F_1^2 and F_1^3,thus $W_{th2}^{R,j} = F_1^1 + F_1^2 + F_1^3$ which is assumed to be greater than $W_{th}^{\max}$. Therefore, the condition of over-granting problem is occurred. Now the OLT calculates the $W_{th2}^{G,j}$ by discarding the smallest frame F_1^3 and $W_{th2}^{G,j} = F_1^1 + F_1^2$ which is smaller than both the $W_{th2}^{R,j}$ and $W_{th}^{\max}$. Here, the smallest frame is discarded to ensure the maximum granted window size without frame fragmentation. The frame F_1^3 is now the unreported frame of thread2, which is denoted by $F_{th2}^{unR,j} = F_1^3$. This $F_{th2}^{unR,j}$ will be granted in the thread1 of time cycle *j*+1 with 1st priority. For maximum *k* number of frames, following formula is used to calculate the granted window size for thread2 of time cycle *j*;

$$W_{th}^{G,j} = F_{th1}^{unR,j} + \sum_{l=1}^{k-S} F_{th2}^l \quad \text{if } W_{th}^{R,j} > W_{th}^{\max} \text{ and } (W_{th}^{R,j} - F_{th2}^{unR,j}) \le W_{th}^{\max} \tag{5.5}$$

Third. In the last buffer status of the time cycle *j*+1, the ONU*1* has one un-granted frame F_1^3 which was already reported in the thread2 of the time cycle *j* and one new frame F_1^1 is also arrived in the buffer. The Report message of the thread1 of the ONU*1* of the time cycle *j*+1 is $W_{th1}^{R,j+1} = F_1^1$. Now the granted window size $W_{th1}^{G,j+1}$ consist of $F_{th2}^{unR,j}$ plus the one or multiple frames from the current $W_{th1}^{R,j+1}$. Therefore, the granted window size for the thread1 of the time cycle *j*+1 is equal to, $W_{th}^{G,j+1} = F_{th2}^{unR,j} + F_1^1$ (assumed that $W_{th}^{\max} \ge F_{th2}^{unR,j} + F_1^1$). The Eq. 5.6 represents the generalized formula to calculate the granted window size for the time cycle j+1 having the unreported frame;

$$W_{th1}^{G,j+1} = F_{th2}^{unR,j} + \sum_{l=1}^{k-S} F_{th1}^{l}$$
$$\text{if } \left(W_{th1}^{R,j+1} + F_{th2}^{unR,j}\right) > W_{th}^{\max} \geq \left(W_{th1}^{R,j+1} - F_{th1}^{unR,j+1}\right) \tag{5.6}$$

To avoid the over-granting problem similar formula is used for the grant allocation process of the entire ONU$_s$ and any number of threads of each ONU.

5.4.3 Large Number of Frame Management for the Proposed Scheme2

When the number of frames in the buffer of an ONU is more than eight, then it is difficult to include the information of all the frames in the Report message of that ONU. Because, according to the MPCP, a Report message can include maximum of 8 frames information at a time [5]. To overcome this problem, we also have proposed a new frame grouping scheme in the proposed Scheme2. Fig. 5.3 illustrates the principle of the proposed frame grouping scheme in the Scheme2.

In the proposed scheme2, we assume that $k > 8$ in a thread of an ONU. In this case, instead of frame by frame information a Report message consists of a group of frames information that is sent to the OLT. Let, m is the number of groups of frame and the value of m must be less than or equal to 8. From the Fig. 5.3 it is clear that each frame group consists of maximum x frames and the FF_{th}^{1}, FF_{th}^{2} to FF_{th}^{m} are the groups of frame in a thread of an ONU. The number of frames in a group may be varied.

Following equations are used to calculate the number of frames in a group and Reports messages, respectively.

$$FF_{th}^{m} = \sum_{l=1}^{x} F_{th}^{l} \quad \text{for } \frac{k}{x} \leq 8 \tag{5.7}$$

$$W_{th}^{R,j} = \sum_{l=1}^{m} FF_{th}^{l} \tag{5.8}$$

Similar to the Eq. 5.6, the granted window size of a thread in a time cycle *j* is calculated by the following equation,

$$W_{th}^{G,j} = \begin{cases} W_{th1}^{R,j} = \sum_{l=1}^{m} FF_{th1}^{l} & \text{if } W_{th1}^{R,j} \le W_{th}^{\max} \\ W_{th2}^{R,j} = \sum_{l=1}^{m-S} FF_{th2}^{l} & \text{if } W_{th2}^{R,j} > W_{th}^{\max} \ge (W_{th2}^{R,j} - FF_{th2}^{unR,j}) \end{cases} \tag{5.9}$$

here, $FF_{th}^{unR,j}$ is the group of unreported frames of a thread of time cycle *j* for an ONU.

The Dp_{th}^{Sent} is sent to the OLT from each ONUs in a thread depends on the number of buffered frames and granted window size $W_{th}^{G,j}$. No frame fragmentation is allowed in the proposed Scheme2, therefore, in a time cycle, the Dp_{th}^{Sent} is same as the $W_{th}^{G,j}$.

5.4.4 Report Message Format for the Scheme2

In the control message scheduling scheme, Report message plays the most vital role to share the upstream channel. Fig. 5.4 shows the Report message format of the proposed Scheme2. Similar to the conventional Report message format, the proposed Scheme2 also uses 2 bytes' queue Report *QR* field. In each *QR* field, a single frame or a group of frames information are comprised.

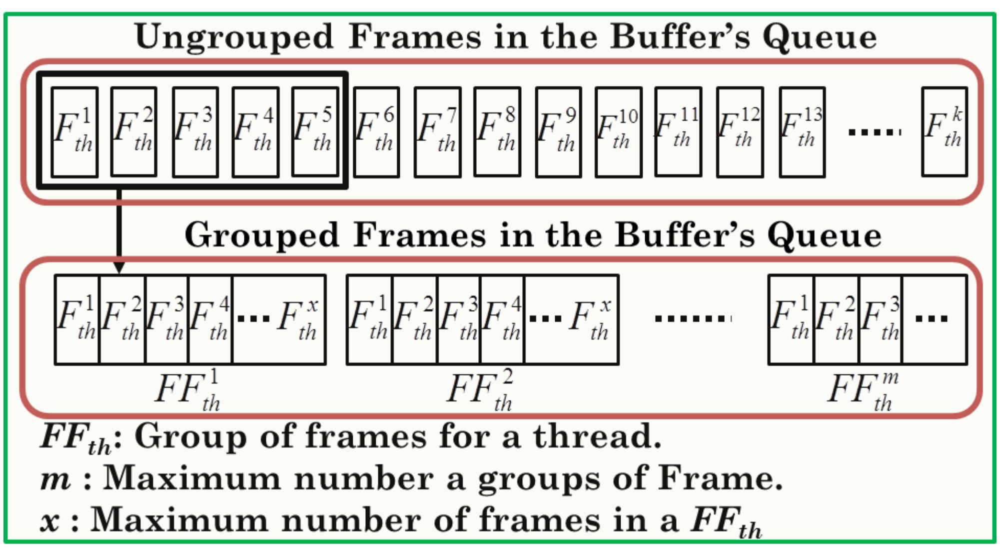

Fig. 5.3 Illustration of frame grouping for large number of frames.

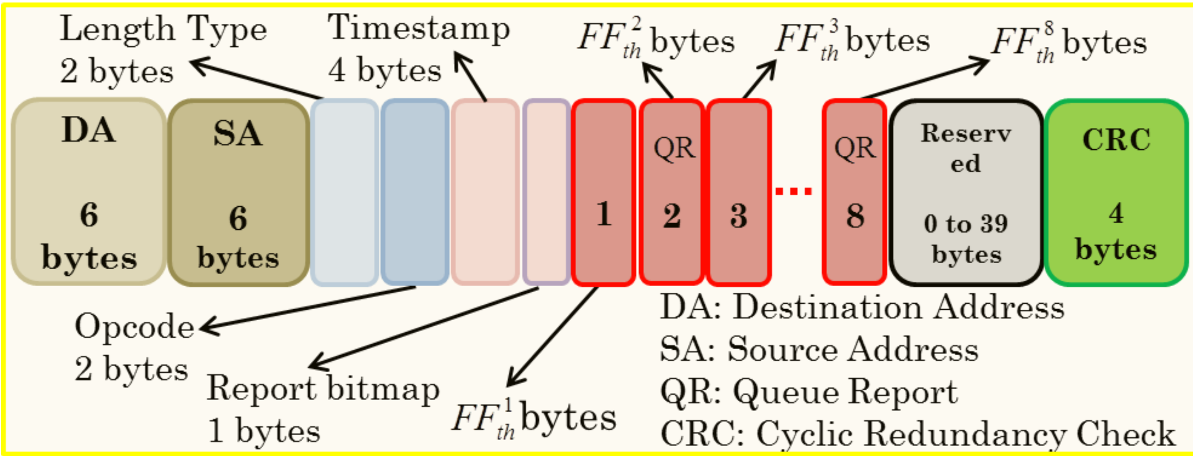

Fig. 5. 4 Report message format for the proposed Scheme2

5.5 Chapter Summary

In proposed Scheme2 of this thesis, a new online MTP based DBA algorithm with proper grant management is introduced to reduce the over-granting problem as well as end to end packet delay of the LR-PONs. We have addressed some of the shortcomings, i.e., over-grating problem, overlapping of timeslots, unused times slots and bandwidth wastage of multi-thread based online DBA algorithms. The proposed algorithm mitigates these problems with lower delay and computational complexity compared to the MTP and E-IPACT schemes.

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CHAPTER VI

PERFORMANCE EVALUATION AND RESULT ANALYSIS

In this chapter, different performance parameters, i.e., average end-to-end packet delay, BWU, over granting rate, computational complexity, and throughput of the proposed DBA schemes for the LR-PON system are evaluated by numerical simulations. Simulation results show the performance of the proposed DBA algorithms. The results of the proposed schemes have been compared with the existing STP, MTP, and E-IPACT schemes.

6.1 Introduction of the Performance Evaluation

This thesis work has considered the LR-PON architecture with 100 km distances between the OLT and ONUs. At each time cycle, maximum 16 active ONUs and single OLT operations were considered. For both the downstream and upstream transmissions 1 Gbps speeds were used. Equal priority based data frames were assumed with first-in first-out (FIFO) principle for each ONU in the network [1]. The buffer occupancy has been considered to be increased with the number of generated packets N_p, which was varied from 0 to 10. The data frames were generated by using highly bursty self-similar network traffic model [2]. The maximum size of a frame was 1500 bytes and DBA processing time was 10 µs. The $T_{Cycle}^{\max}$ was varied from 1.0 ms to 4.0 ms with non-uniform offered loads. The simulation parameters that were used in this paper are summarized in Table 6.1 [3].

6.2 Delay Analysis of the Proposed Schemes

To evaluate the end-to-end packet delay we have considered three different delays, i.e., the granting delay D_{th}^{G}, queuing delay D_{th}^{Q}, and polling delay D_{th}^{P} per thread, for the proposed and existing MTP based DBA algorithms. In the usual PON system, the D_{th}^{G} in ms is equal to the RTT [4] which is calculated by using Eq. 6.1;

$$D_{th}^{G} = RTT = \frac{d\ (km)}{204.260\,(\mathrm{m}/\mu\mathrm{s})} \tag{6.1}$$

here, *d* is the distance between the OLT and ONUs in *km*.

Table 6.1 Simulation Parameters

Symbol	Quantity	Value
N	Total number of ONUs	16
d	Distance between OLT and ONUs	100 km
n	Total number of threads	2
S_{EOH}	Size of Ethernet overhead	576 bits
S_R	Size of Report message	304 bits
S_F	Maximum size of a frame	1500 bytes
$T_{Cycle}^{\max}$	Maximum length of a time cycle	1 to 4 ms
R	Transmission speed	1 Gbps
k	Maximum number of frames in a thread	4
N_P	Number of generated packets	0 to 10
T_{Gd}	Guard interval	5 µs
T_{GS}	Grant scheduling time	10 µs

The queuing delay of a thread is directly dependent on the length of W_{th}^{G} and data transmission speed in the PON system. In contrast, the average D_{th}^{P} is the half of the T_{Cycle} and it is dependent on the data packet length and data transmission speed.

$$D_{th}^{P} = T_{th}^{pkt} + T_{th}^{OH} = (R \times Dp_{th}^{Sent}) + T_{Gd} + T_{th}^{R} \tag{6.2}$$

here, *R* is the data transmission speed, Dp_{th}^{Sent} is the amount of data bytes sent by an ONU in a thread, T_{th}^{R} is the transmission time of a Report message, T_{th}^{pkt} is the transmission time of a packet in the upstream direction, and T_{th}^{OH} is the overhead in time for a thread.

The total packet delay, i.e., end-to-end packet delay, D_{th}^{T} of a thread for the proposed DBA schemes can be calculated by equation (6.3),

$$D_{th}^{T} = D_{th}^{G} + D_{th}^{Q} + D_{th}^{P} \tag{6.3}$$

6.3 Throughput Analysis of the Proposed Schemes

Throughput is the prime parameter used to represent the performance of any communication network. It provides the overall successful data reception rate in respect of total transmitted data [5]. For *N* ONUs in the LR-PON and *n* number of threads, the following equation is used to calculate the throughput:

$$Th = \frac{\sum_{i=1}^{N} W_i^{ST}}{\sum_{i=1}^{N} W_i^{GT}} \tag{6.4}$$

here, *Th* is the throughput in the LR-PON, W_i^{GT} is the total grants of different threads of the ONU *i*, i.e., $W_i^{GT} = \sum_{th=1}^{n} W_{th}^{G}$, in a time cycle, and W_i^{ST} is the summation of transmitted windows of different threads of the ONU *i*, i.e., $W_i^{ST} = \sum_{th=1}^{n} Dp_{th}^{Sent}$, in a time cycle.

6.4 Analysis of the Bandwidth Utilization for the Proposed Scheme

The BWU of the LR-PON system is the ratio of granted window size to the transmitted window size. Here, the transmitted window size is the summation of granted windows and overheads in the LR-PON system. According to the proposed DBA schemes we can calculate the BWU using the following equations,

$$BWU = \frac{\sum_{i=1}^{N} W_i^{GT} - \sum_{i=1}^{N} W_{th}^{OH\_T}}{\sum_{i=1}^{N} W_i^{GT}} \tag{6.5}$$

Here, $W_i^{OH\_T}$ is the summation of overheads for different threads of the ONU *i*, i.e., $W_i^{OH\_T} = \sum_{th=1}^{n} W_{th}^{OH}$, in a time cycle.

6.5 Analysis of Over-Granting Problem

The efficiency of any DBA algorithm of the LR-PON depends on the reduction of this over-granting problem [6]. The amount of total over-granted window sizes W_T^{OG} of the LR-PON system in a time cycle for the proposed DBA schemes can be expressed by Eq. 6.6;

$$W_T^{OG} = \sum_{i=1}^{N} W_i^{OG\_T} \tag{6.6}$$

Here, $W_i^{OG\_T}$ is the amount of over-granted window size for different threads of the ONU *i* in a time cycle. Following equation is used to calculate the $W_i^{OG\_T}$ in a time cycle.

$$W_i^{OG\_T} = \sum_{th=1}^{n} (W_{th}^{G} - Dp_{th}^{Sent}) \tag{6.7}$$

The over-granting rate of a thread can be defined as the ratio of the over-granted window size to the granted window size by the OLT. The following equation is used to determine the over-granting rate R_T^{OG} of the LR-PON;

$$R_T^{OG} = \frac{\sum_{i=1}^{N} W_i^{OG\_T}}{\sum_{i=1}^{N} W_i^{G\_T}} \tag{6.8}$$

6.6 Analysis of Computational Complexity

The existing E-IPACT scheme can reduce the over-granting problem. However, it requires involving both the OLT and ONUs in the DBA processing that significantly increases the computational complexity. So, in a time cycle, the total computational complexity β_T of the existing E-IPACT scheme can be expressed by following formula;

$$\beta_T = N^G \times \beta_{OLT} + N^R \times \beta_{ONU} \tag{6.9}$$

Where, N^G is the number of Gate messages for N ONUs, β_{OLT} is the computational complexity of the OLT for processing each Gate message, N^R is the number of Report messages for N ONUs, and β_{ONU} is the computational complexity of an ONU.

In the proposed DBA algorithms, only the OLT is involved in the DBA processing. In a time cycle, the total computational complexity β_T can be expressed by the following formula;

$$\beta_T = N^G \times \beta_{OLT} \tag{6.10}$$

6.7 Simulation Results Analysis for the Proposed Schemes

In this section, simulation results are presented to show the performance of the proposed DBA algorithms for the LR-PON system. We also have compared the results of the proposed schemes with those of the existing STP [6], MTP [7], and E-IPACT [8] schemes. For representing the simulation results we have used contour plots in addition to the comparisons by graphs for different offered loads and cycle times. In the contour plots, lighter colors represent better performance for any performance parameter presented in the paper.

6.7.1 Comparison of Average End-to-End Packet Delay

In the Figs. 6.1 and 6.2, this work compare the average packet delay in ms with respect to different offered loads for the LR-PON, i.e., maximum distance is 100 Km, and conventional PON, i.e., maximum distance is 20 Km, respectively. Both the Figures show the comparison results of the existing STP, MTP, E-IPACT and proposed DBA schemes for 2 ms cycle time. From both the Figures it is clear that with the increase of the reach, i.e., distance between the OLT and ONUs, the average packet delays for all the schemes are increased.

However, the proposed schemes provide lower packet delays than the existing schemes for both the PON systems, i.e., LR-PON and conventional PON. In the LR-PON system, shown in the Fig 6.1, the highest end to end packet delay of the proposed DBA schemes is 0.83 ms, whereas the highest end to end packet delays in the STP, MTP and E-IPACT schemes are 2.17 ms, 1.48 ms and 1.01 ms, respectively. So, it is clear that the proposed DBA schemes provide approximately 62%, 43%, and 18% lower end-to-end packet delay than the STP, MTP and E-IPACT schemes, respectively. Similarly, for the 20 km PON system, shown in the Fig 6.2, the proposed DBA scheme provides approximately 73%, 56%, and 26% lower end-to-end packet delay compared to the existing STP, MTP and E-IPACT schemes. So from these two results it is clear that the proposed schemes provide lower end-to-end packet delay than the existing schemes for both the cases of the LR-PON and conventional PON systems.

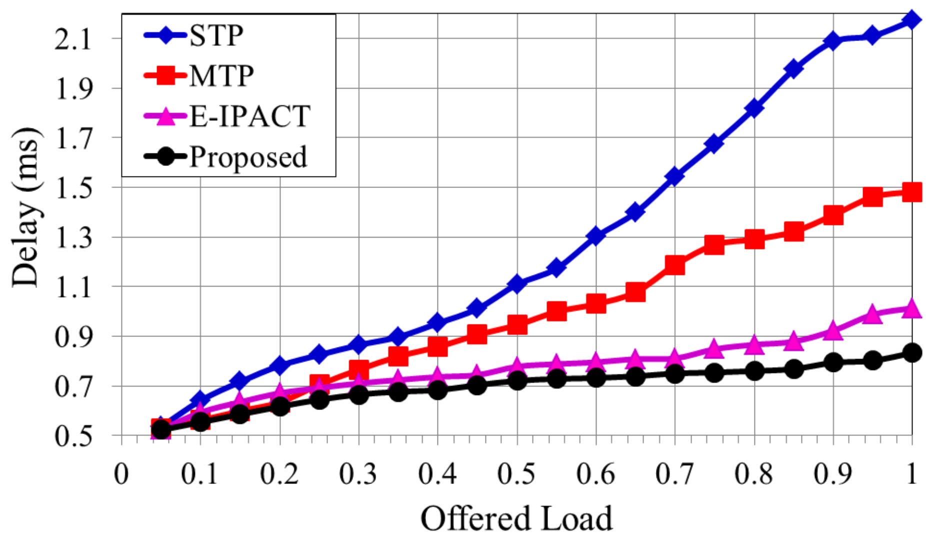

Fig. 6.1 Comparison of average packet delay for the LR-PON with 2 ms cycle time.

Contour plots in Figs. 6.3 to 6.6 show the end-to-end packet delays vs. offered loads for different cycle times, i.e.,1 ms to 4 ms, of the STP, MTP, E-IPACT, and proposed schemes, respectively. From the contour plots it is clear that the maximum delay for the proposed schemes is 0.8 ms whereas the maximum delays in the E-IPACT, MTP, and STP schemes are 0.85 ms, 1.4 ms, and 2.2 ms, correspondingly. These contour plots show that the proposed schemes provide lower packet delay than all other existing schemes for any value of cycle time and offered load.

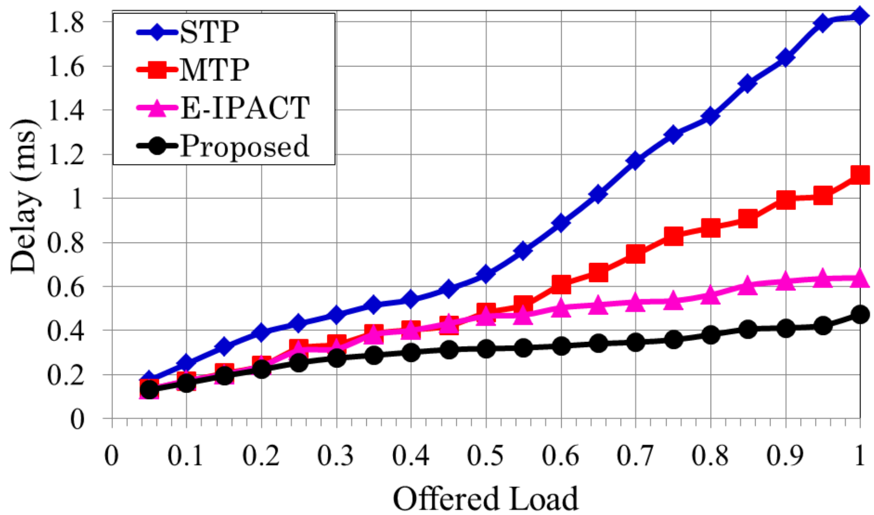

Fig. 6.2 Comparison of average packet delay for PON with 2 ms cycle time.

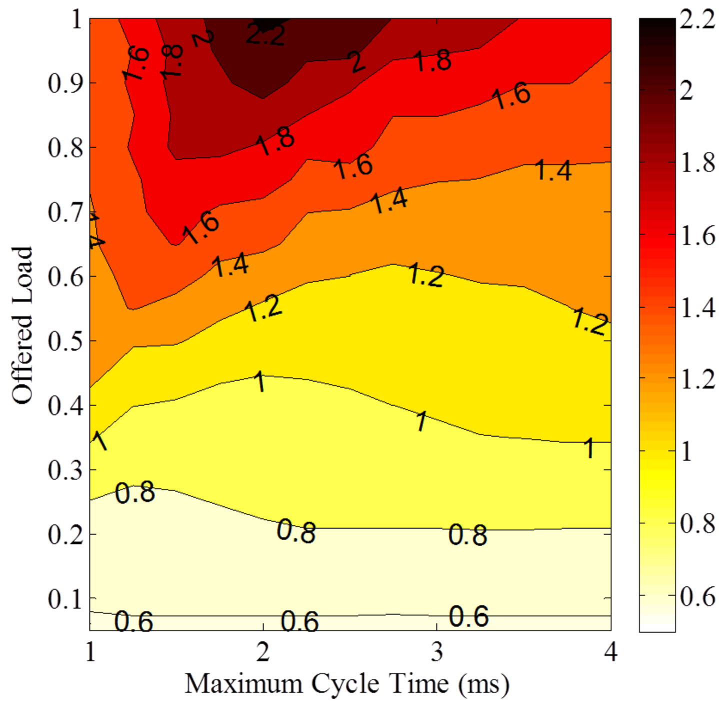

Fig. 6.3 Average packet delay of the STP scheme for different cycle times and offered loads of the LR-PON.

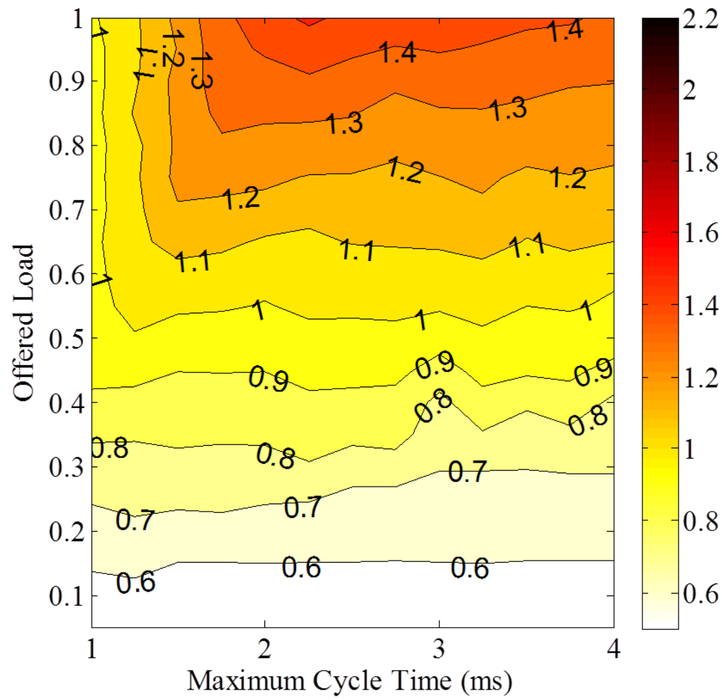

Fig. 6.4 Average packet delay of the MTP scheme for different cycle times and offered loads of the LR-PON.

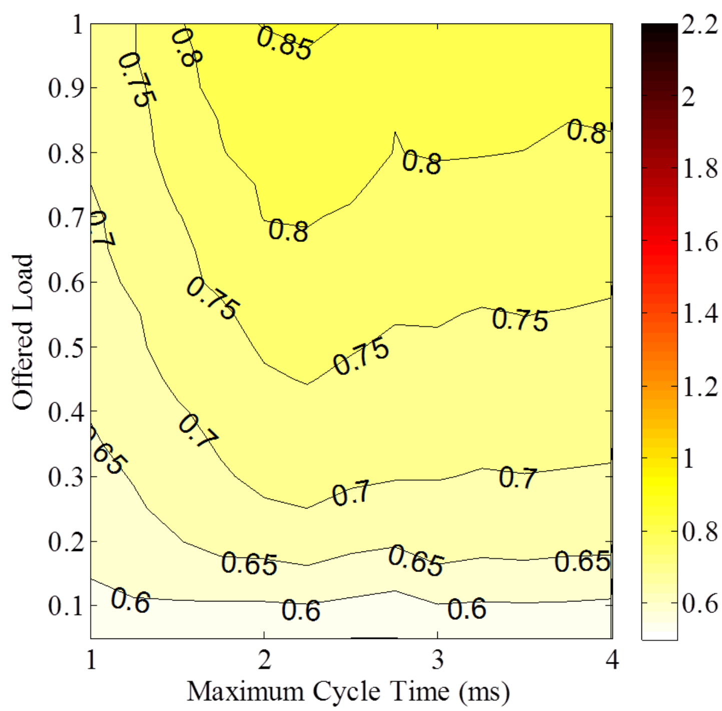

Fig. 6.5 Average packet delay of the E-IPACT scheme for different cycle times and offered loads of the LR-PON.

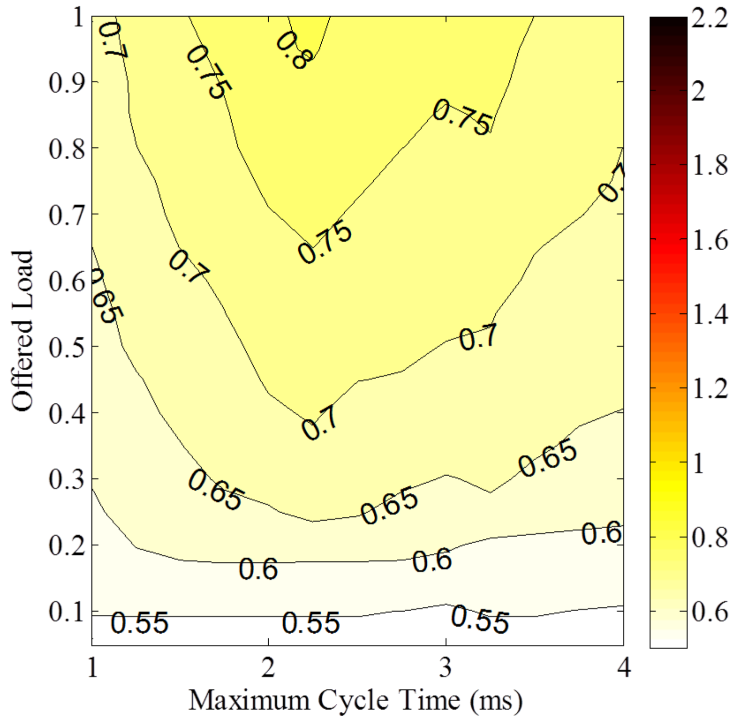

Fig. 6.6 Average packet delay of the proposed schemes for different cycle times and offered loads of the LR-PON.

6.7.2 Comparison of the BWU

Fig. 6.7 shows the comparison of BWU for 2 ms cycle time among the MTP, E-IPACT and proposed DBA schemes. In comparison of BWU the proposed schemes provide better performance than the existing schemes for the entire duration of the offered loads, i.e., 0.1 to 1.0. At the highest offered load of 1.0, the proposed DBA schemes provide almost 90% BWU. In contrast, at the highest offered load of 1.0 the existing MTP scheme provides 88% and the E-IPACT scheme provides 83% BWU. Figs. 6.8, 6.9 and 6.10 show the BWU by contour plots of the existing MTP, E-IPACT, and proposed DBA schemes, respectively. As shown in the Fig. 6.10, the proposed schemes provide more than 90% BWU for the cycle times higher than 2 ms and offered loads higher than 0.2.

In contrast, the existing E-IPACT scheme provides more than 90% BWU, shown in the Fig. 6.9, for cycle times higher than 3.5 ms and offered loads higher than 3.0. Similarly, the existing MTP scheme provides more than 90% BWU; shown in the Fig. 6.8, for cycle times higher than 2.5 ms and offered loads higher than 0.2. The E-IPACT scheme provides the lowest area of BWU higher than 90% because the E-IPACT scheme uses extra bandwidth for transmitting the $W_{th}^{\max}$ in each thread.

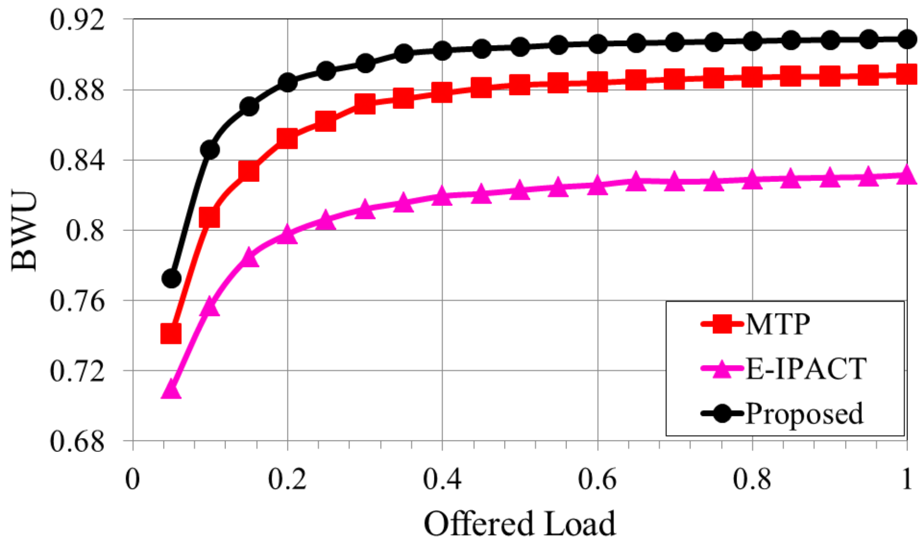

Fig. 6.7 Comparison of BWU for the LR-PON system with 2 ms cycle time.

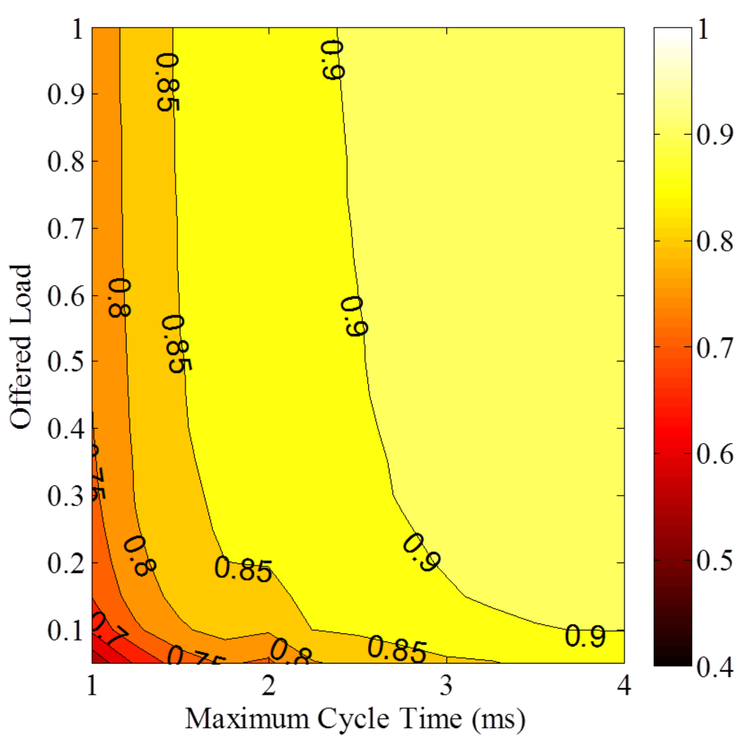

Fig. 6.8 BWU of the MTP scheme for different cycle times and offered load of the LR-PON.

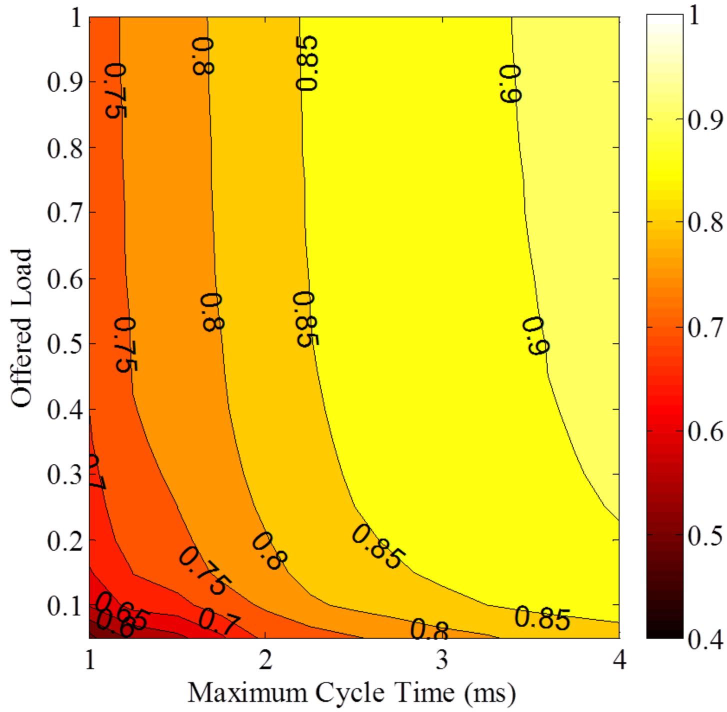

Fig. 6.9 BWU of the E-IPACT scheme for different offered loads and cycle times of the LR-PON.

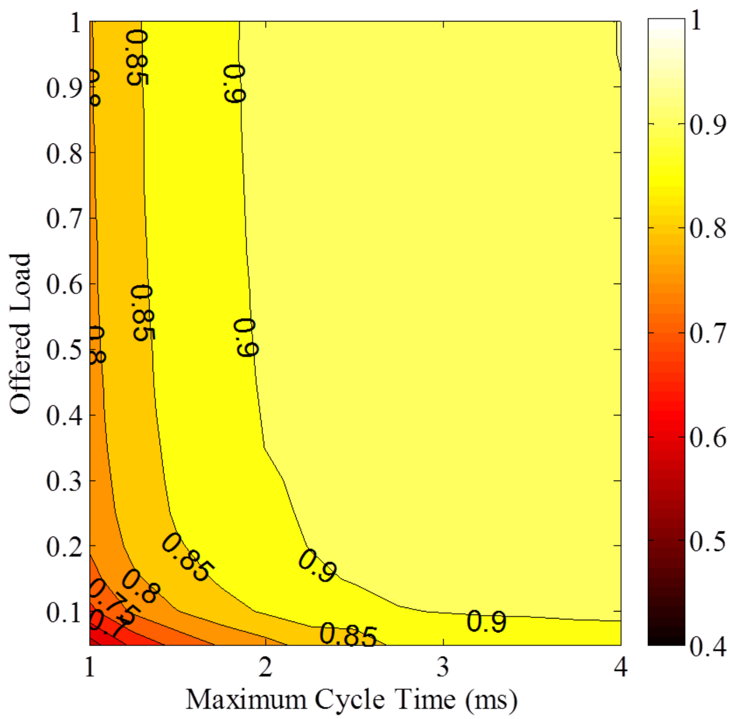

Fig. 6.10 BWU of the proposed schemes for different cycle times and offered loads of the LR-PON.

6.7.3 Comparison of Over-granting Rate for the LR-PON

Fig. 6.11 shows the comparison of over-granting rate vs. offered loads of the three different schemes for 2 ms cycle time. From the Fig. 6.11 it is clear that the over-granting rate is increased with the offered loads. The conventional MTP scheme provides the worst over-granting rate of 28% for the maximum offered load of 1.0. Whereas, at the offered load of 1.0 the existing E-IPACT and proposed DBA schemes provide only 6% and 3% over-granting rate, respectively. Figs. 6.12, 6.13 and 6.14 represent the over-granting rate by using contour plots for different cycle times and offered loads of the existing MTP, E-IPACT and proposed DBA schemes, respectively. From the analysis of contour plots, it can be seen that the maximum over-granting rate of the MTP, E-IPACT and proposed DBA schemes are 49%, 21% and 12%, respectively. Both the existing E-IPACT and proposed schemes provide equal value of lowest over-granting rate of 2%. However, the proposed schemes provide wider area of 2% over-granting rate than the E-IPACT scheme in both the direction of offered loads and cycle times.

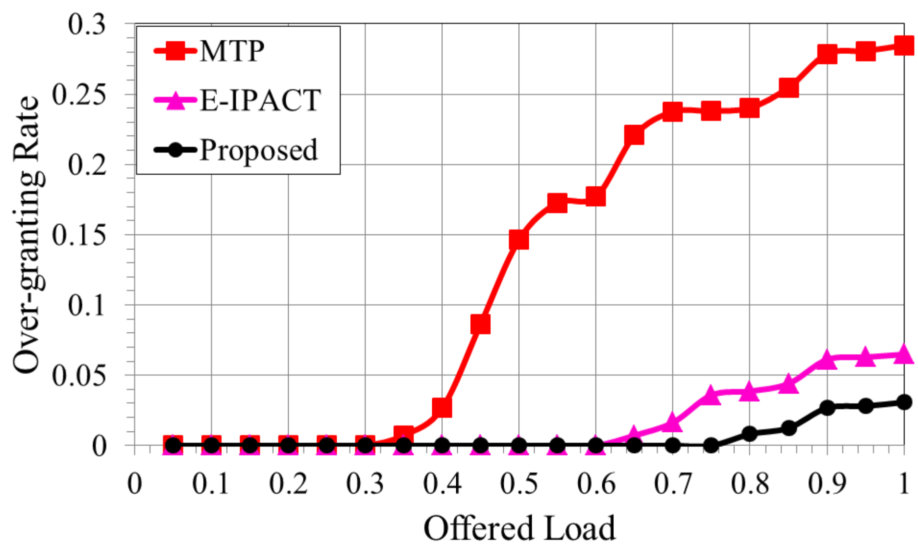

Fig. 6.11 Comparison of over-granting rate for the LR-PON system with 2 ms cycle time.

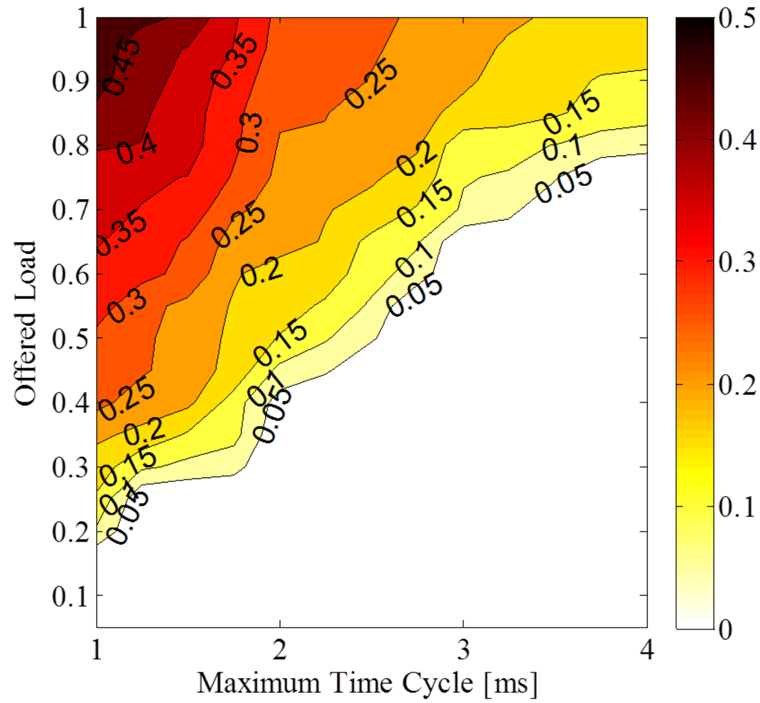

Fig. 6. 12 Over-granting rate of the MTP scheme for different offered loads and cycle times of the LR-PON.

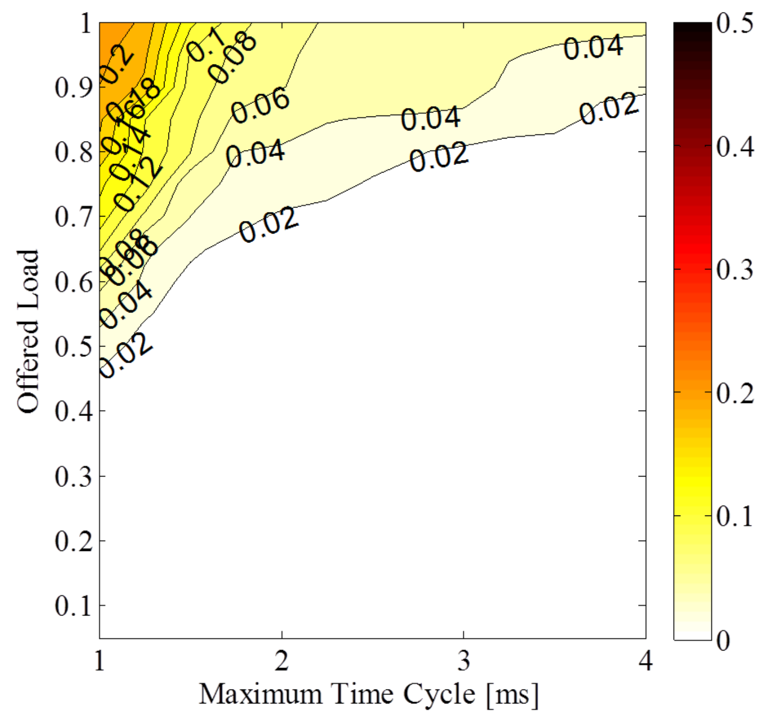

Fig. 6.13 Over-granting rate of the E-IPACT scheme for different cycle times and offered loads of the LR-PON.

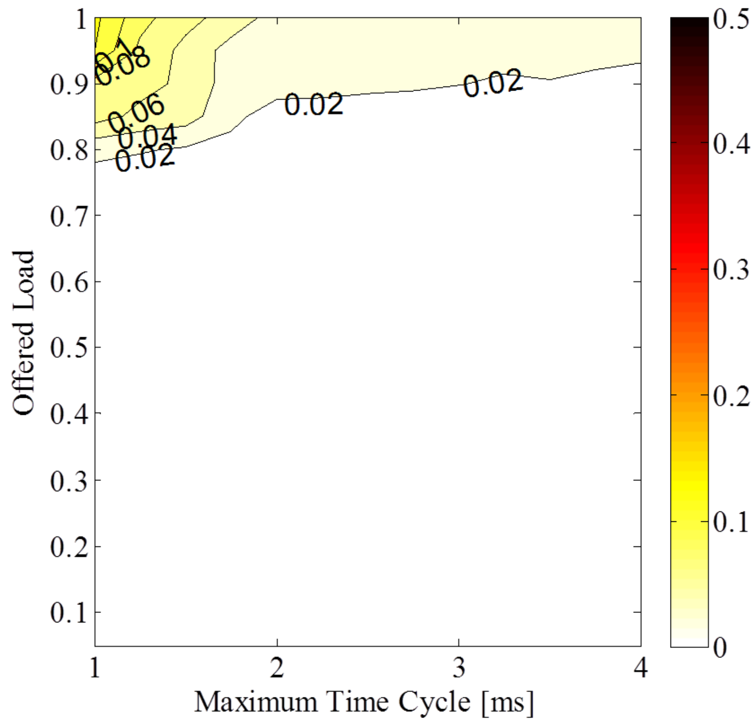

Fig. 6. 14 Over-granting rate of the proposed schemes for different cycle times and offered loads of the LR-PON.

6.7.4 Computational Complexity for the LR-PON

The comparison of computational complexity in µs vs. offered loads of the existing E-IPACT and proposed DBA schemes for the LR-PON system are shown in Fig. 6.15. Both the proposed and existing schemes require almost equal computational time for the lower offered loads because in these offered loads minimum numbers of Report and Gate messages are involved in the DBA process. For the maximum offered load of 1.0, the existing E-IPACT scheme requires almost 964 µs of computation time. In contrast, for the same offered load, the proposed DBA scheme requires 452 µs computation time. Fig. 6.15 shows that the proposed DBA scheme offers lower computational complexity compared to the existing E-IPACT scheme.

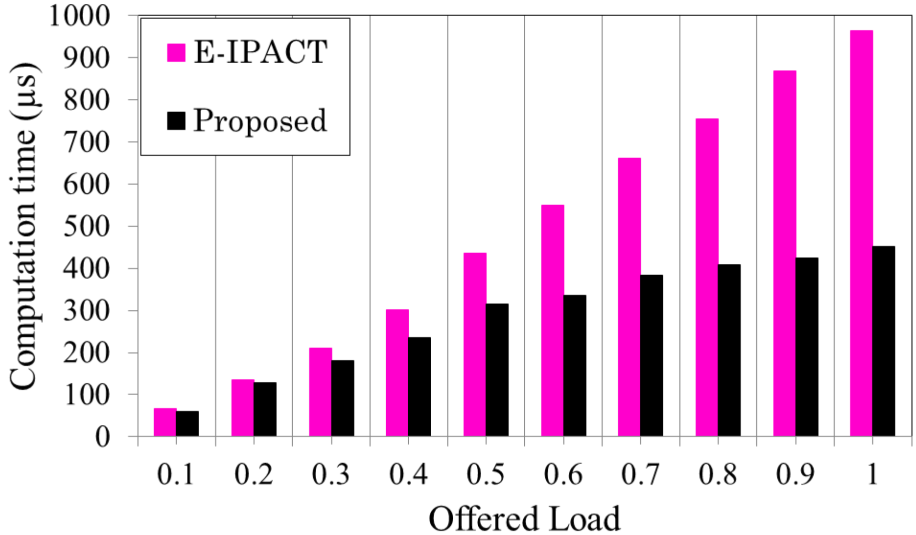

Fig. 6.15 Comparison of computational complexity for E-IPACT and proposed DBA schemes.

6.7.5 Comparison of Throughput for the LR-PON

In Fig. 6.16, we compare the throughput vs. offered loads of the three different schemes for 2 ms cycle time. It is shown that at the higher offered loads, the proposed DBA schemes provide better throughput performance compared to the existing MTP and E-IPACT schemes. At the highest offered load of 1.0, the existing MTP and E-IPACT schemes provide the throughput of 72% and 80%, respectively. Whereas, at the highest offered load of 1.0 our proposed DBA schemes provide about 88% throughput. From the contour plots of Figs. 6.17, 6.18, and 6.19, it is clear that the proposed schemes provide wider area of throughput higher than 80% compared to the existing MTP and E-IPACT schemes. Moreover, the proposed DBA schemes provide more than 90% throughput for cycle times larger than 2.5 ms. However, both the existing schemes never achieve the throughput higher than 90%. The main reason of the lowest throughput in the existing schemes is the over-granting problem which is increased with increasing the offered loads.

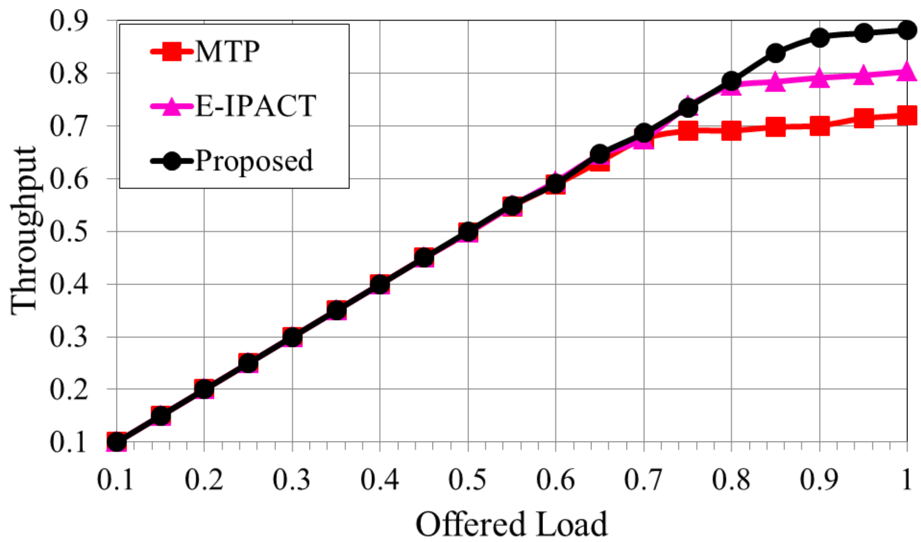

Fig. 6.16 Comparison of throughput for the LR-PON system.

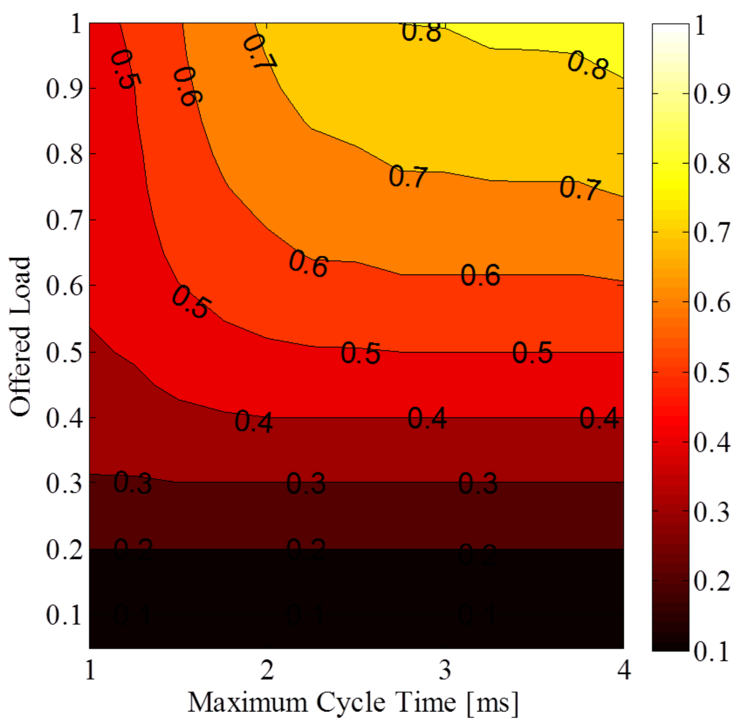

Fig. 6.17 Throughput of the MTP scheme for different cycle times and offered loads of the LR-PON.

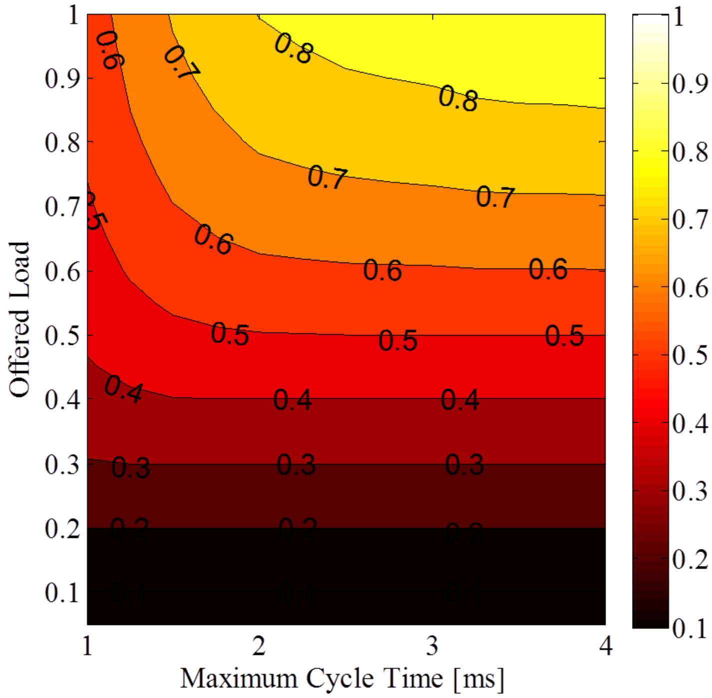

Fig. 6.18 Throughput of the E-IPACT scheme for different cycle times and offered loads of the LR-PON.

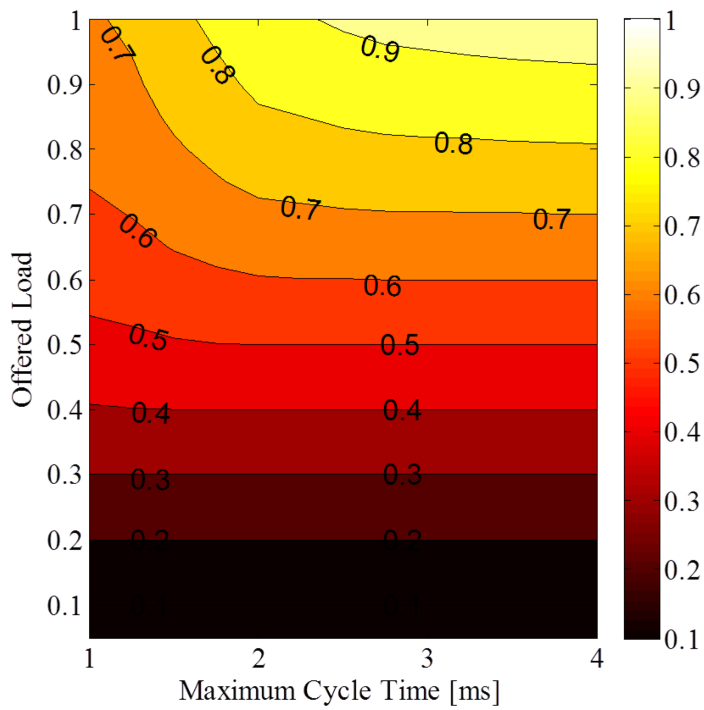

Fig. 6.19 Throughput of the proposed schemes for different cycle times and offered load of the LR-PON.

6.8 Chapter Summary

A new approach of control message scheduling algorithm is incorporated in Scheme1 called SMGP that can reduce almost 43% of the end to end packet delay than the existing MTP based DBA algorithms at the highest offered load of 1.0. The proposed DBA Scheme2 can mitigate the over-granting problem with 53 % lower computational complexity compared to the existing E-IPACT DBA scheme. In the Scheme2, we also have proposed a new approach for managing the large number of frames with modified Report message format to optimize the DBA schemes for better QoSs of the LR-PON system. The performances of the proposed and existing DBA schemes for the LR-PON system are evaluated and compared by using numerical simulations. The simulation results show that for different offered loads and cycle times the proposed DBA schemes provide better performances compared to the existing STP, MTP, and E-IPACT schemes in terms end to end packet delay, BWU, over-granting rate, computational complexity, and throughput. Therefore, these results show that the proposed schemes can ensure the enlargement of the LR-PON system with better QoSs.

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CHAPTER VII

CONCLUSION

The objective of this thesis is to design new multi thread polling based dynamic bandwidth allocation schemes for the LR-PON which proficiently mitigates the over-granting problem with lower computational complexity and lead to reduce the average end-to-end packet delay with better BWU. We have investigated different MTP based DBA schemes for finding a solution which ensures improved QoSs with respect of the existing schemes. These improved QoSs are evaluated in terms of average packet delay, BWU, over-granting rate, computational complexity, and throughput.

7.1 Summary

In this thesis, two new MTP based DBA schemes are proposed, i.e., Scheme1 also called SMGP and Scheme2. The proposed Scheme1 is based on a new multi thread control messages scheduling approach and fair bandwidth allocation among different priority based ONUs. Regarding the control messages scheduling approach, some enrichment has been introduced in this work such as multiple Gate sending at a time, utilization factor to perform the bandwidth allocation based fair on-demand, which leads to improve both the average end-to-end packet delay and BWU of the available bandwidth for the LR-PON system. In the proposed scheme2, each ONU will send the frame information instead of total buffer occupancy to avoid the over-granting problem. Scheme2 can mitigate the over-granting problem with 53% lower computational complexity compared to the existing E-IPACT DBA scheme. In the Scheme2, we also have proposed a new approach for managing the large number of frames with modified Report message format to optimize the DBA schemes for better QoSs of the LR-PON system. Buffers' modeling, report message format for the proposed scheme2 are also discussed in this thesis work. The combined effect of the scheme1 and scheme2 effectively improves the overall QoSs of the LR-PON system. The simulation results show that for different offered loads and cycle times the proposed DBA schemes provide better performances compared to the existing STP, MTP, and E-IPACT schemes in terms end to end packet delay, BWU, over-granting rate, computational complexity, and throughput.

Simulation analysis shows that the proposed DBA schemes (scheme1+scheme2) provide approximately 62%, 43%, and 18% lower end-to-end packet delay than the STP, MTP and E-IPACT schemes, respectively for the LR-PON system. The proposed DBA schemes provide almost 90% BWU. In contrast, at the highest offered load of 1.0, the existing MTP scheme provides 88% and the E-IPACT scheme provides 83% BWU. The conventional MTP scheme provides the worst over-granting rate of 28% for the maximum offered load of 1.0. Whereas, at the offered load of 1.0, the existing E-IPACT and proposed DBA schemes provide only 6% and 3% over-granting rate, respectively. For the maximum offered load of 1.0, the existing E-IPACT scheme requires almost 964 μs of computation time. In contrast, for the same offered load, the proposed DBA scheme requires 452 μs computation time. The comparison of throughput vs. offered loads of the three different schemes for 2 ms cycle time, it is shown that at the higher offered loads, the proposed DBA schemes provide better throughput compared to that of the existing MTP and E-IPACT schemes. At the highest offered load of 1.0, the existing MTP and E-IPACT schemes provide the throughput of 72% and 80%, respectively. Whereas, at the highest offered load of 1.0 our proposed DBA schemes provide about 88% throughput. In this thesis work, the numerical results also shown in using contour plot analysis for different offered loads and different time cycle for observing the effects of heavily loaded condition as well as cycle time variations.

In the past few decades there has been a revolution in computing and communications, and all indications are that technological progress and use of information technology will continue at a rapid pace. Nowadays, the optical technology scales up both in the bandwidth and transmission speed as a result the user, cost, distance and power consumption become the freezing factors in the modern network architecture. The LR-PON architecture reduces the number of COs by a single one that reduces the overall network deployment cost. So, the LR-PON system can supports large number of users with limited active equipment for reducing the deployment cost. This thesis work proposed two schemes for reducing the delay of the LR-PON system and mitigates the over-granting problem that ensures effective BWU and lower packet drop condition. So we think, if it can be implemented in the LR-PON technology, users on the different services will enjoy more bandwidth with higher transmission speed in the optical access networks.

7.2 Future Work

The proposed MTP based DBA schemes are evaluated in terms of limited number of ONUs and thread. For real time performance analysis the number of ONUs must be more than 16 in the LR-PON system. Thread tuning is important for MTP schemes. In our proposed schemes, there is no thread tuning performance analysis. So, in the nearest future, the ONUs number for the LR-PON system will be increased to observe the overall performance. Number of thread will be varied for same offered load and different MTP based DBA schemes. In the recent research progress, communication securities have achieved a great concern. Several hardware-accelerated protection schemes for the LR-PON system were proposed. In this thesis work, there is actually no concern about the network protection. So, in the nearest future, we have a great interest to implement the proposed schemes with high protection based protocol. In this regard, we think the future users can enjoy their communication services with higher security.

One of the limitations of this work is that, for high number of ONU such as 1024 to 2048, this simulation analysis was not evaluated. When the number of ONU will increase the system bandwidth allocation scheme will be also increased. This complexity may be affecting the overall DBA schemes for LR-PON system. In my future work, I will increase the ONU from 256 to 1024 and observe the result analysis. If the data speed increased to 10 Gbps or more form 1 Gbps, the overall performance also vary according to the transmission speed. In LR-PON system, the round trip time (RTT) depends on the transmission speed. If transmission speed increases then the RTT will decreases and the overall end to end packet delay also reduced. However, it is important to observe the throughput and over-granting rate for high transmission speed.

List of Publications

International Conferences:

[1] **S. Saha** and M. Hossen, "Scheduled Multi Gate Polling Algorithm for Delay Reduction of Long Reach PON based Access Network," in *Proc. of Int. Conf. on Advances in Electrical Engineering*, Bangladesh, 2017.

[2] **S. Saha** and M. Hossen, "An Efficient Multi-Thread Polling based DBA Algorithm for Solving the Over-Granting Problem of Long-Reach PON," in *Proc. of Int. Conf. on Electrical & Electronic Engineering*, 2017.

[3] M. Hossen and **S. Saha**, "Thread Guaranteed Algorithm for Real Time Traffic in Multi-Threaded Polling of PON-based Open Access Network," *in Proc. of Int. Conf. on Electrical, Computer and Communication Engineering*, Bangladesh, 2017.

[4] M. D. Chaity, M. Hossen, and **S. Saha**, "An Efficient Intra Thread Scheduling based Decentralized Online Multi Thread Polling Scheme for Improving QoSs of PON," in *Proc. of Int. Conf. on Advances in Electrical Engineering*, Bangladesh, 2017.

[5] N. S. Usha, M. Hossen, and **S. Saha**, "Efficient Duty Cycle Management for Reduction of Energy Consumption in Wireless Sensor Network," in *Proc. of Int. Conf. on Electrical & Electronic Engineering,* 2017.

International Journal (Submitted):

[1] **S. Saha** and M. Hossen, "Efficient DBA Algorithms for Reducing Delay and Solving the Over-Granting Problem of Long Reach PON," Under Peer Review in the *IEEE/OSA Journal of Optical Communications and Networking*, 2017.