Architectures and Dynamic Bandwidth Allocation Algorithms for Passive Optical Hybrid Networks

March 2014

Monir Hossen

Architectures and Dynamic Bandwidth Allocation Algorithms for Passive Optical Hybrid Networks

山梨大学大学院
医学工学総合教育部
博士課程学位論文

March 2014

Monir Hossen

Architectures and Dynamic Bandwidth Allocation Algorithms for Passive Optical Hybrid Networks

Supervised by
Prof. Masanori Hanawa

A thesis submitted in fulfillment of the requirement for the award of the PhD degree

Interdisciplinary Graduate School of Medicine and Engineering
University of Yamanashi, Japan
March 2014

Monir Hossen

This thesis is dedicated to my beloved wife, son, mother, and father for their absolute love, encouragement, and expectation on me.

Acknowledgement

First of all, I am indebted to almighty Allah, because the almighty made me to be a part of that group of people who are inherently ambitious and courageous to face the challenges of the modern technological development.

I would like to express the deepest appreciation and gratefulness to my supervisor, Prof. Masanori Hanawa for his valuable guidance, advice and crucial contribution from the very early stage of this research and for getting admission to this University as a PhD student. In addition, he provided me steady encouragement, excellent academic guidance, and supports in various ways during my study period as a research student. It has been a great pleasure to have him as my PhD supervisor. He has provided me a significant contribution to trigger my intellectual maturity that will be benefited me for a long time. I am also grateful to his family for providing every support to survive me and my family in Japan.

I gratefully acknowledge all the members of my PhD dissertation committee for reviewing this dissertation and providing some constructive comments. I am thankful to them that in the midst of all activities, they have agreed to be one of the members of the evaluation committee.

I am heartily thankful to Japan student service organization (JASSO) and Rotary Yonyama scholarship foundation for providing me a scholarship throughout my study period in Japan. I am also obliged to the authority of University of Yamanashi and Japanese government for giving me the opportunity to study in Japan.

It is a pleasure for me to pay tribute to the authority of Khulna University of Engineering & Technology (KUET), Bangladesh for providing me the study leave to study in the University of Yamanashi, Japan.

I would like to thank my beloved wife, son, mother, father, brothers, relatives, teachers, and friends for their continuous love, sacrifice, encouragement, and faith in me during my study period in Japan.

Collective and individual acknowledgements are also owed to all the members of the Internetworking and Communication Systems Lab., Dr. Okamura, Dr. Nakamura, Mr. Hagihara, Mr. Iijima, Mr. Mizukami, Mr. Mizukoshi, and Mr. Matsushita for their friendship and enormous help during last three years. I was exceptionally fortunate and grateful in having Dr. Okamura, Mr. Hagihara, Mr. Iijima, and Mr. Mizukami for their enormous help and friendly cooperation and sharing various thoughts during the discussion.

Finally, my thanks go in particular to Dr. Ahsan Habib, Dr. Jahangir Masud and his family, Dr. Mridul Kanti Mandal and his family, Mr. Matiur Rahman, Mr. Obaidur Rahman, Mr. Mirza Rubel and his wife, Mr. Mukter Hossain, Mr. Anwar Hossain, Mr. Rana and other friends in Japan for their valuable suggestions, company, and help during my PhD study, as well as expressing my apology that I could not mention personally one by one.

Table of Contents

List of Figures

List of Tables

Abstract

A passive optical network (PON) based hybrid network is a highly capable access network that effectively converge several service providers without suffering from any bandwidth deficiency. Main considerable points to design an efficient PON-based hybrid network are; an effective network architecture for combining several service providers with their own features in a single PON and a suitable dynamic bandwidth allocation (DBA) algorithm. This thesis proposes several PON-based hybrid network architectures, i.e., a single-optical line terminal (single-OLT) PON-based fiber to the home (FTTH) and wireless sensor networks (WSNs), a multi-OLT PON-based FTTH and WSNs, a multi-OLT PON-based open access networks (M-OANs), and a multi-OLT and multi-wavelength PON-based OANs (MM-OANs). A PON-based hybrid network consisting of a single OLT for the multiple service providers increases the computational complexity of data packet processing in the OLT, resulting in a longer time delay and more packet losses. To overcome these problems this thesis proposes a multi-OLT PON-based hybrid networks for reducing the computational complexity of data packet processing in a hybrid network of the multiple service providers. One of the most important issues on designing the hybrid PON is the improvement of bandwidth sharing efficiency in the upstream channel among the multiple service providers having different packet lengths and data rates. In addition to the new architectures of the PON-based hybrid networks this thesis also proposes several new DBA algorithms, i.e., adaptive limited DBA1 (ALDBA1) and ALDBA2 algorithms for the single-OLT PON-based hybrid networks, and an ALDBA algorithm for the multi-OLT PON (ALDBAM) based hybrid networks. All these algorithms consider different maximum upstream transmission windows for the different service providers in the network. The size of a maximum transmission window for a service provider depends on its maximum packet length. The proposed ALDBAM scheme is a modified version of the ALDBA schemes, where both the ALDBA1 and ALDBA2 schemes are combined with proper guard time management and a modified version of the multi-point control protocol (MPCP) in the medium access control layer.

In the usual OANs, several service providers are connected to a single access terminal and the users are able to get any service from those service providers by using a single access terminal. That means the OAN provides a true broadband concept. In this thesis, the proposed M-OAN uses a single PON-based access network with multiple OLTs for the multiple service providers and the proposed MM-OAN uses a single PON-based access network with the multiple OLTs and multiple uplink wavelengths for the multiple service providers. The OLTs of the proposed PON-based OANs are considered as the central offices (COs) while all the ONUs of the proposed PON-based OANs are considered as the access terminals for all the service providers. The multiple OLTs in the M-OAN share the computational complexity of data packet processing from the multiple service providers that reduces the data processing times as well as the end-to-end packet delay and improves the bandwidth utilization. In addition to those advantages in the M-OAN, the MM-OAN also uses multiple uplink wavelengths where a single upstream channel is successfully overlapped by the simultaneous transmissions of the multiple service providers that improve the upstream efficiency and throughput.

All the proposed DBA algorithms for the PON-based hybrid FTTH and WSNs and the network structures of the OAN of this thesis are studied by laboratory made computer simulation programs. The performances of the ALDBA1 and ALDBA2 schemes are evaluated for a single-OLT PON-based hybrid networks combining the FTTH and WSNs while a multi-OLT PON-based hybrid FTTH and WSNs is considered for the ALDBAM scheme. On the other hand, four different service providers, i.e., FTTH, WSN, high definition television or video on demand, and femto networks are considered in the performance analysis of both the M-OAN and MM-OAN architectures by using a modified version of the limited service (LS) scheme. This thesis also provides some quantitative comparisons among the performances of the proposed and existing DBA schemes even though it is difficult and not fair because the network architectures and simulation environments are not similar among them. The simulation results show that the proposed DBA schemes with the proposed hybrid network architectures of the PON, and the proposed PON-based OANs with a modified version of the LS scheme provide lower packet delay and jitter with higher bandwidth utilization, higher upstream efficiency, and higher throughput than the conventional LS scheme of both the PONs and OANs, respectively. When the performances of the proposed ALDBAM scheme are compared to those of the LS scheme it is found that the ALDBAM scheme provides more than 115% less delay with 40% higher throughput than those of the LS scheme for an offered load of 1.0 and a 2-ms cycle time. On the other hand, the MM-OAN provides more than 400% higher throughput with 50% lower jitter than the single-OLT PON-based OAN for an offered load of 1.0 and a 2-ms cycle time. These results and macro view comparisons with the existing schemes prove the significance and validity of these researches of this thesis.

Key words: hybrid networks, PON, WSN, OAN, FTTH, DBA algorithm, packet delay, jitter, upstream efficiency, bandwidth utilization, and throughput.

1. Introduction

This chapter starts with a brief definition of the passive optical network (PON) based hybrid networks. Next, the necessity of the hybrid networks for combining several service providers in a single network architecture with the importance of a new dynamic bandwidth allocation (DBA) algorithm fit for the proposed hybrid network architectures are explained that lead to the motivations of this thesis. Finally, the outline of this thesis is presented.

1.1 What is Hybrid Networks

A hybrid network is a new network concept in the modern information and communication arena. In a hybrid network, two or more different networks or service providers are combined all together with their own features and infrastructures. The hybrid network is a more real life networking topology as it provides reliable and versatile connections and data transmission paths to the users [1]. It provides less installation cost by sharing a single backbone network instead of installing separate network infrastructures for the different networks or service providers.

In a hybrid network, the central office (CO) provides independent connection with the different networks or service providers. That means, in the hybrid network, data transmission of a service provider does not depend on the other service providers. As a result, failure of data transmission from a service provider does hamper the performance of other service providers in the network.

The main drawbacks of a hybrid network are that it is complicated and difficult to diagnose any fault in the network. To overcome the fault diagnosis problem in the hybrid network, intelligent hubs are designed to provide automatic fault isolation and processing [1].

In this thesis, a PON-based hybrid networks is considered where two service providers, i.e., fiber to the home (FTTH) and wireless sensor networks (WSNs), are combined with their own features and infrastructures. This thesis also considers a PON-based open access network (OAN) where four different service providers, i.e., FTTH, WSNs, high definition television or video on demand (HDTV/VoD), and Femto networks (FNs), are comprised with their own features and infrastructures.

1.2 Necessity of the Hybrid Networks

The ubiquitous city (u-City) is an autonomous city. In a u-City, all the information systems and service providers are virtually interlinked together. The convenience of a u-City is that anyone can access any service provider from anywhere in the city by using only one access terminal. Nowadays, the number of different service providers, e.g., FTTH [2,3], WSNs, local area networks (LANs), FNs [4], HDTV/VoD [5,6], and ad-hoc networks, in a u-City has increased dramatically. Although a significant number of service providers providing both the wireless and fiber-based networks already exist in the modern cities, still there is no suitable interlink between the wireless and fiber-based operators. Usually, sensor nodes in a WSN will send notifications to the CO concerning any abnormality of any household or commercial device in a sensor network that is expected to be deployed for all the households and commercial systems in the u-City, e.g., gas systems, temperature and pressure monitoring systems, electric sparking and smoke detection systems, automobile systems, and medical sensor nodes in a hospital. Usually, the WSN service providers use wireless links to connect wireless sensor nodes to a CO, i.e., personal area network coordinator (PANC). In contrast, the optical fiber-based access networks are used for the FTTH terminals. This optical fiber-based network infrastructure has enough bandwidth and that bandwidth can be effectively shared with a WSN without any bandwidth bottlenecks occurring in the access networks. In this case, a cluster-based WSN is important to divide the whole network into several clusters. Moreover, clustering of a WSN effectively reduces the total energy consumption in the network [7,8,9,10]. Figure 1.1 shows an illustrative example of a cluster-based WSN. J. Tang et al. have proposed using a cluster-based WSN to divide the entire sensor network of a u-City and to connect all of the static cluster heads (CHs) to the PANC through a radio-over-fiber (RoF) link [11]. In the RoF based sensor networks static CHs are required to connect the CHs to the fiber. M. Hossen et al. have proposed a cooperative clustering algorithm, where each cluster contains a static CH and each CH is connected with the optical network

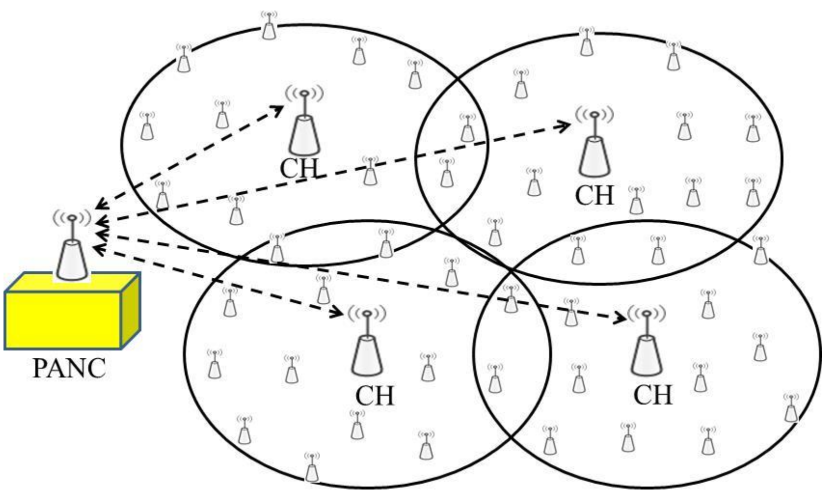


Fig. 1.1 Illustrative example of a cluster-based WSN.

units (ONUs) of a PON system through an optical fiber link [12,13]. As the sensor nodes are deployed in a u-City, any sensor node in a home or office can act as a static CH and easily be incorporated into the electric supply system. That is why there is no possibility of an inadequate power supply, unlike the CHs of a typical sensor network. The use of the optical fiber links in a cluster-based WSN in a u-City is very convenient because it will avoid long distance radio frequency (RF) transmissions [12,13], i.e., from the CHs to the PANC, which will reduce the energy consumption of the small battery powered sensor nodes [14].

Moreover, the HDTV/ VoD and FNs in addition with the FTTH and WSNs are also going to be more popular in a modern city. However, constructing a closed, specific-use network for each individual service provider and accommodating several users using different access terminals and servers require an enormous amount of time and expense. To overcome the enormous expense and deployment of several backbone networks, a PON-based hybrid network is an effective solution to comprise all the service providers in a single optical network, because the PON systems can effectively share the upstream channel and the CO equipment over a high-speed and high-capacity bandwidth demands [9]. Also a PON is an inherently cost-effective technology [15] because it does not require active components and remote power facilities. Furthermore, sharing the fiber medium for the several service providers reduces the cost of physically deploying the fiber.

One of the most critical issues for converging the FTTH access networks and several service providers, e.g., WSNs, HDTV/VoD, FNs etc., in a single optical line terminal (single-OLT) PON is the requirement of more computational complexity of data packet processing in the OLT. Because all of these service providers in a u-City have several features, e.g., device capacity diversity, application diversity, mobility, numbering and routing diversity, security, and privacy, they significantly differ from the conventional access networks. This is why the current access network architectures are not capable of integrating these service providers efficiently [16]. To mitigate this problem, some polling algorithms have been proposed to allow additional time in the OLT for computation and management in addition to the guard time between the transmitted data packets from every two successive ONUs [17]. However, this thesis provides a detail PON-based hybrid network architecture that contains multiple OLTs [18, 19, 20] in the CO in addition to the PON-based hybrid network with a single OLT [21] to reduce the computational complexity of data packet processing in the OLT. To show the effectiveness and validity of the proposed time division multiplexing (TDM) PON-based hybrid networks in practical applications new DBA algorithms are required for both the single-OLT and the multi-OLT hybrid PONs. This thesis also presents several new DBA algorithms for the different proposed PON-based hybrid network architectures. The Ethernet-based data packets and TDM-PON principles are considered in all the analysis of this thesis.

1.3 Bandwidth Allocation Algorithm in PON

In the PON systems, each ONU's upstream bandwidth is decided by allocating time slots specified by the OLT in unit time [22]. Interleaved polling algorithm [13] is a widely used algorithm in which the OLT polls the ONUs individually and issues Gate messages to them in a round-robin fashion. In this algorithm, the OLT maintains a polling table containing the number of bytes waiting in each ONU's buffer and round-trip-time (RTT) to each ONU. At the end of an upstream transmission window, every ONU informs its queue size to the OLT by a Report message. The main principle of this algorithm is to provide synchronization among the data transmission instants from the multiple ONUs to avoid data collision and to fairly share the upstream channel capacity. The bandwidth allocation algorithm has a major impact on minimizing latency, improving the fairness of bandwidth sharing efficiency, meeting the quality of service (QoS) guarantees, and requirement of buffer size in the upstream direction. In a general sense, bandwidth allocation algorithms can be classified into two major groups; fixed bandwidth allocation (FBA) and DBA algorithms.

1.3.1 Fixed Bandwidth Allocation (FBA) Algorithm

The FBA scheme is a very simple bandwidth allocation algorithm. In the FBA scheme, the OLT ignores the requested window sizes from the ONUs and always grants the maximum transmission windows to all the ONUs, as a result a cycle time T_{cycle} is a constant for any traffic condition in every time cycle [23]. Here, the T_{cycle} is a length of a polling cycle in the upstream time cycle of a PON system. The T_{cycle} in a PON is defined by the summation of the granted transmission windows to all the ONUs and total over heads. In this scheme, all traffics are considered to be a single class traffic.

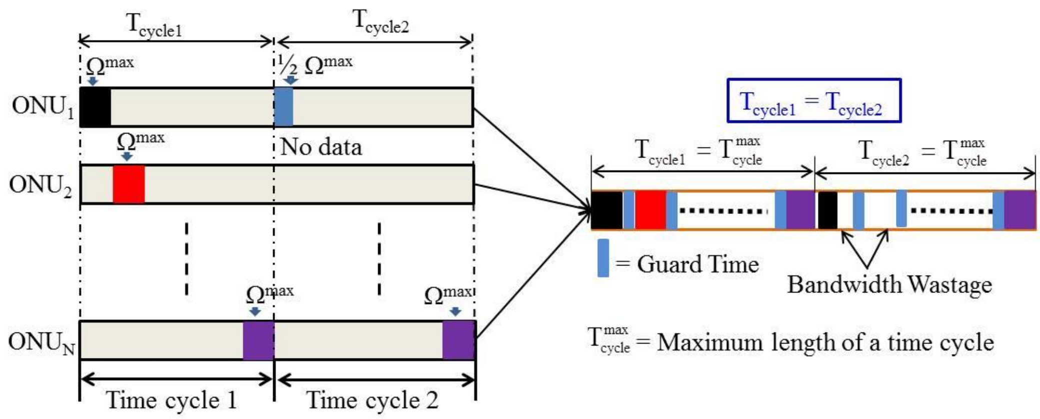


Fig.1.2 Illustrative example of an FBA scheme.

Figure 1.2 shows the illustrative example of an FBA scheme. The main advantages of this scheme are that it requires very low computational complexity and very simple logical operations. However, the main drawbacks of this algorithm are lightly loaded ONUs, the ONUs those have smaller data packets in the queue, will under utilize their allocated bandwidth leading to increase the end-to-end packet delay to other ONUs and eventually deteriorate the throughput and bandwidth utilization of the system. From the Fig. 1.2 it is obvious that the length of the 1st time cycle T_{cycle1} is equal to the $T_{cycle}^{\max}$ where every ONU has a maximum transmission window to transmit. On the other hand, the length of the 2nd time cycle T_{cycle2} is also equal to the $T_{cycle}^{\max}$ even though the ONU1 has half of the $\Omega^{\max}$ and the ONU2 does not have any data to transmit. As a result, some bandwidths are wasted in the 2nd time cycle.

1.3.2 Dynamic Bandwidth Allocation (DBA) Algorithm

The DBA algorithms are playing a vital role in distributing the upstream bandwidth to the ONUs of a PON system. The DBA algorithms are suitable for the burst network traffics such as the FTTHs and voice over internet protocol (VoIP). In the DBA schemes, the transmission window of each ONU is upper bounded by the $\Omega^{\max}$[24]. When the requested bandwidth by the ONU is less than the $\Omega^{\max}$, the OLT grants the requested bandwidth; otherwise, $\Omega^{\max}$ is granted.

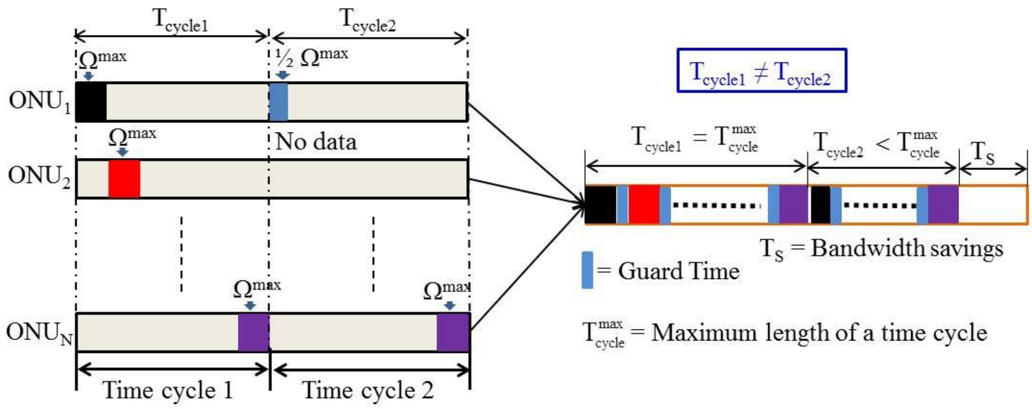


Fig. 1.3 Illustrative example of a DBA scheme.

Figure 1.3 shows an example of bandwidth allocation in a PON using a DBA scheme. In the DBA schemes, since the granted window to an ONU is based on the requested window by that ONU, the T_{cycle} is variable. As shown in the figure, the cycle time in the 1st time cycle is $T_{cycle\,1} = T_{cycle}^{\max}$, because every ONU has requested for the maximum bandwidth $\Omega^{\max}$. In contrast, the cycle time in the 2nd time cycle is $T_{cycle\,2} = T_{cycle}^{\max} - T_S$, here, T_{S} is the cycle time savings due to the lightly loaded ONUs. This scheme reduces the bandwidth wastage by granting smaller bandwidth to the lightly loaded ONUs. However, one limitation of this algorithm is that making the T_{cycle} too small will cause lower bandwidth utilization, ratio of effective data to the effective data plus overheads, because of the constant guard time between every two successive ONUs and this occurrence is called the light-load penalty. Following equations represent the light-load penalty effect in the PON system using the existing LS DBA scheme:

$$T_{cycle} = \frac{N\Omega^{grant} + NB_C}{R_U} \tag{1.1}$$

$$BWU = \frac{N\Omega^{grant}}{N\Omega^{grant} + NB_C} \tag{1.2}$$

where, N represents the number of ONUs, Ω^{grant} is the granted window size for an ONU in a time cycle, R_U is the transmission speed, B_C is the overhead, i.e., summation of the guard intervals, Ethernet overheads, and Report messages, and BWU is the bandwidth utilization.

From the Eq. 1.1 it is clear that the length of a T_{cycle} depends on the total granted window size in a time cycle as the total overhead NB_C and transmission speed R_U are constant in every time cycle. Hence, the smaller T_{cycle} means the smaller total granted windows, i.e., $N\Omega^{\text{grant}}$, and the smaller $N\Omega^{\text{grant}}$ means lower BWU as shown in the Eq. 1.2.

1.3.3 Comparisons Between the FBA and the DBA Algorithms

In the FBA scheme, a T_{cycle} is a constant for all the traffic loads in every time cycle. In this case, data packets suffer from the same delay in every time cycle and it does not depend on the present network traffics. So, it is clear that the length of the T_{cycle} for the FBA scheme is always equal to the $T_{cycle}^{\max}$. If the traffic load is very low then the bandwidth utilization problem will be severe in the FBA scheme due to the bandwidth wastages by the Ethernet overheads, Report messages, and guard times. The following formula represents the length of a cycle time for the PON system using the FBA scheme.

$$T_{cycle} = T_{cycle}^{\max} = \frac{N(B_{rep} + GI) + N(B + B_{eth})P^{\max}}{R_U} \tag{1.3}$$

where, B_{rep}, B, and B_{eth} denote the Report message size, data packet size, and Ethernet overhead, respectively, GI is the guard interval, N represents the number of ONUs, $P^{\max}$ indicates the maximum number of data packets in an ONU.

In the DBA scheme, the T_{cycle} is variable under the low and non-uniform traffic conditions, since the granted window size for an ONU is based on the requested window size by that ONU. The bandwidth utilization in the DBA scheme is better than that of the FBA scheme due to avoidance of the bandwidth wastages. Equation 1.4 represents the cycle time for the DBA scheme.

$$T_{cycle} = \frac{N(B_{rep} + GI) + \sum_{i=1}^{N}(B + B_{eth})P_i}{R_U} \tag{1.4}$$

where, P_i is the number of data packets in the queue of the ONU i and $P_i \leq P^{max}$.

Table 1.1 shows comparisons between the FBA and DBA schemes in a PON system at a glance. These comparisons show for the non-uniform self-similar network traffics.

Table 1.1 Comparisons between the FBA and DBA schemes

Quantity	FBA	DBA
Efficiency	Inefficient	Very efficient
Jitter	Lower	Higher
Bandwidth utilization	Lower	Higher
Throughput	Lower	Higher
Traffic condition	Not suitable for burst traffic	Suitable for burst traffic
Allocated bandwidth	Constant	Dynamic
Complexity	Simple	Complicated

1.4 Thesis Outline

This thesis organized in 8 chapters. Figure1.4 shows the thesis outline in short using a block diagram. In the chapter 2, some theoretical frameworks are explained that is related to the proposed research works. This chapter provides some background on the different PONs and DBA algorithms for general understanding of them. Chapter 3 presents the architectures of the proposed single-OLT and multi-OLT PON-based hybrid networks for comprising the FTTH and WSNs. Chapter 4 provides detailed analysis of the proposed DBA algorithms for the hybrid PONs. Chapter 5 elucidate the performance parameters, methodologies, and comparisons of the proposed DBA schemes to the existing schemes for providing sufficient contributions, significance, and validity of this research. Chapter 6 illuminates two new architectures of the proposed PON-based OANs. In the chapter 7, simulation results of the proposed PON-based OANs have been analyzed using the modified version of the LS scheme. Finally, chapter 8 concludes this thesis by explaining the finding of this research and its importance for the future communication professionals.

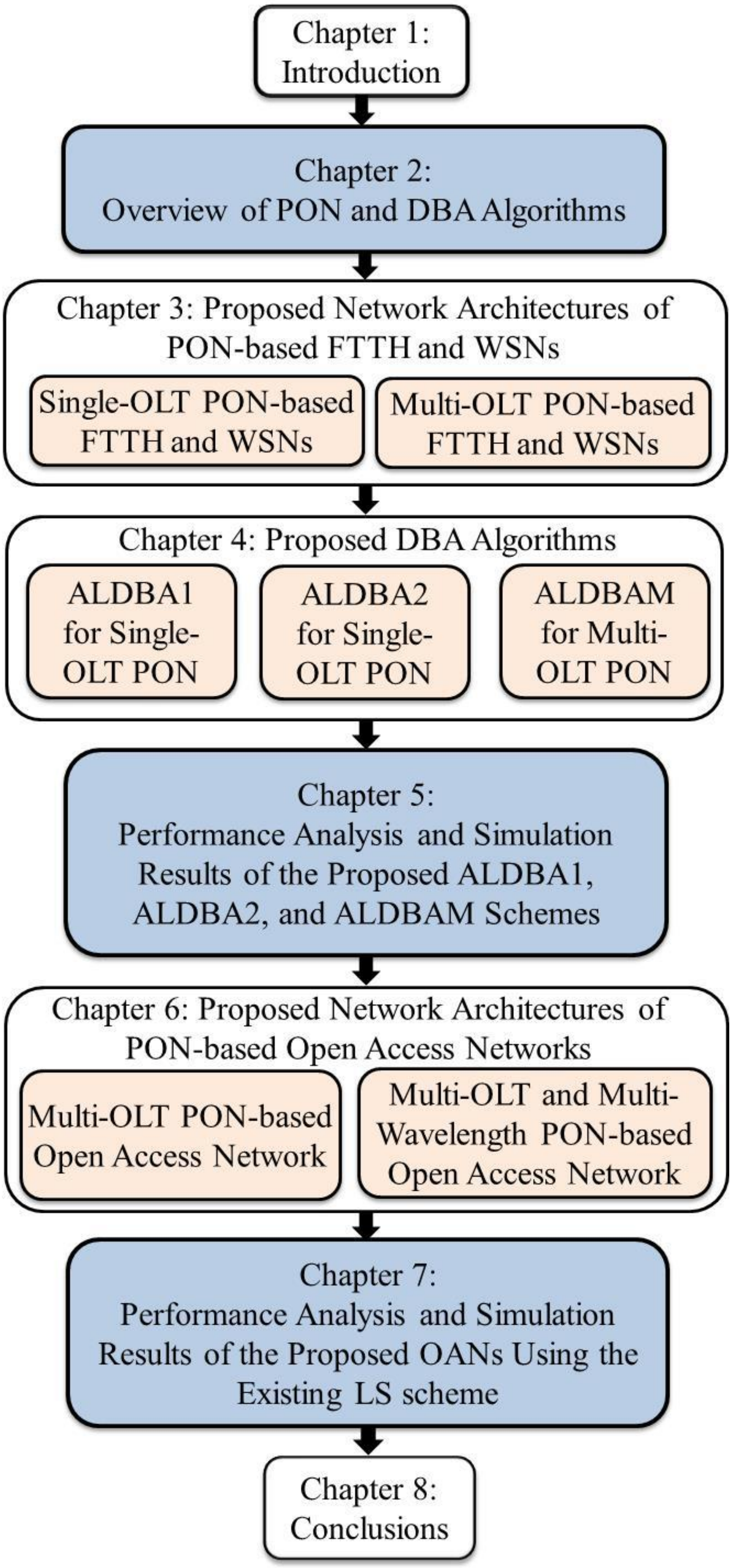


Fig. 1.4 Outline of the thesis.

2. Overview of PONs and DBA Algorithms

PON is an inherently cost effective technology in the modern communication arena. Application of the PON technology in the communication arena is getting more and more popular due to its bandwidth intensiveness. The DBA algorithm provides a significant contribution in achieving the optimum performance of a PON system. This chapter presents a brief review of the existing PONs and several DBA algorithms.

2.1 PONs

In a PON system, no active elements are used between the CO and the end users in the network, i.e., OLT and ONUs. A PON only contains passive optical components, e.g., optical fibers, combiner/splitters, between the two end points of the network. A PON can be deployed in several network topologies, e.g., tree, ring, and bus [25]. However, tree topology is the most popular one in the PON deployment, where an OLT will be at the root and all the ONUs will be at the tree side [26]. Multiple ONUs are connecting to an OLT through 1:*N* splitter/combiner. The PON provides bi-directional transmissions between the OLT and ONUs through a single optical fiber link. The MPCP [14, 27] plays a vital role in the avoidance of collisions and the sharing of the single optical fiber link with the multiple ONUs in a tree-based PON topology.

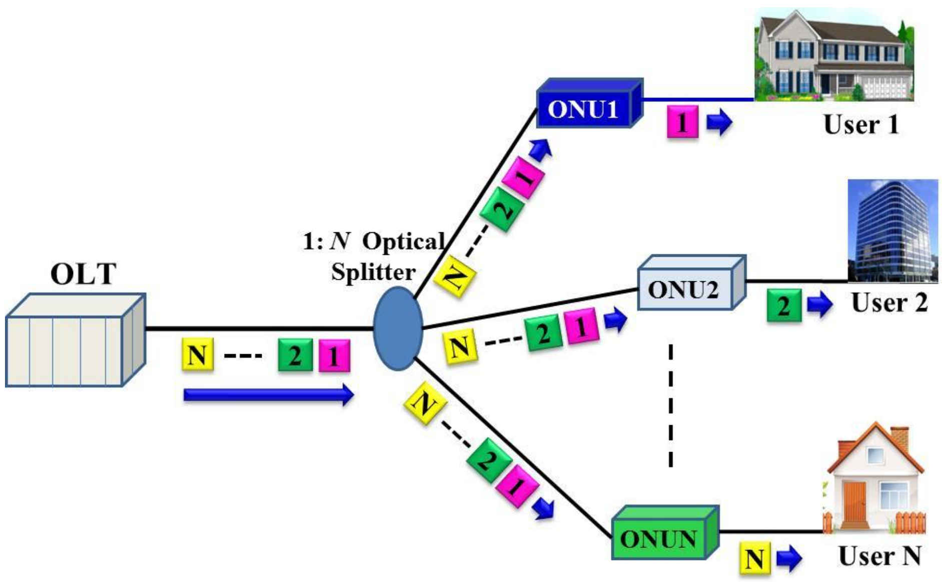


Fig. 2.1 Downstream transmissions in a PON.

In the downstream direction of a PON, data transmission is broadcasting in nature, i.e., point to multi-point (P2MP), where the Gate messages and data packets are broadcasted from the OLT to all the ONUs. Each ONU accepts the Gate message and data packets from the OLT according to the destination address. Figure 2.1 shows the downstream data transmission in a PON system. Here, an OLT broadcasts the downstream data packet to the *N* ONUs connected to the FTTH terminals. The downstream data packets from the OLT are multiplexed in a TDM principle. The main information contained in a downstream packet is the upstream transmission time and the length of the transmission window of each ONU.

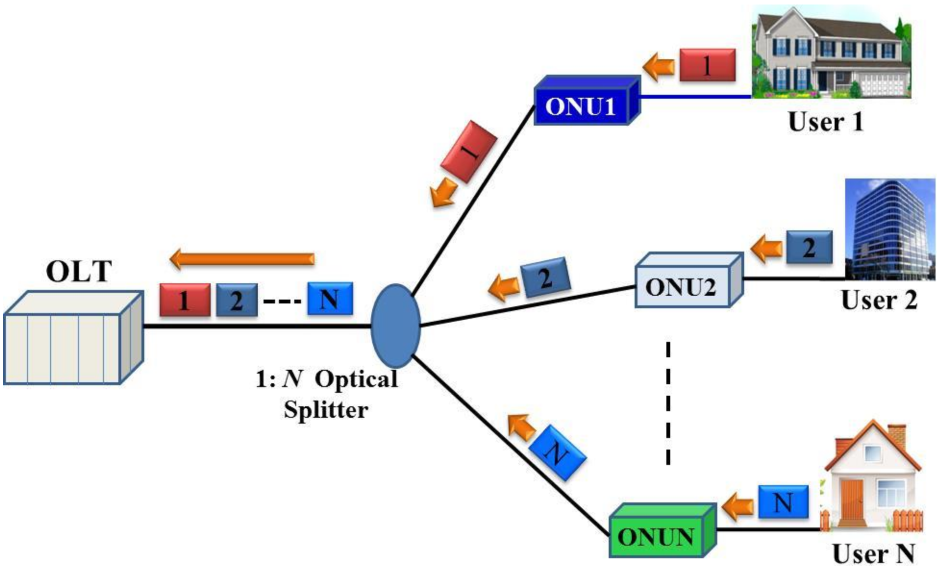


Fig. 2.2 Upstream transmissions in a PON.

In an upstream direction, a PON is a multi-point to point (MP2P) network [23] where all the ONUs share a common channel to transmit their data packets to the OLT. Figure 2.2 shows the upstream data transmission in a PON system. Here, every ONU transmits its upstream data packets in a specific time slot allocated by the OLT. The upstream data packets from the entire ONUs are combined together in the splitter/comber and then transmit to the OLT.

Data transmissions of a PON in both the upstream and downstream directions are controlled by a DBA algorithm and the MPCP. The MPCP is a two-way messaging protocol defined to arbitrate the simultaneous transmissions of different ONUs and resides at the medium access control (MAC) layer. The MPCP relies on two control messages, Report and Gate, in its regular operation. In this protocol, auto discovery mode is used to connect and detect a newly activated ONU in the network and to calculate the RTT delay and to assign the MAC address of that ONU. In the MPCP of the PON system, the RTT is used to schedule the control messages: the Gate message from the OLT to ONUs and the Report message from the ONUs to the OLT. The RTT depends on the physical distance from the OLT to an ONU and the OLT maintains a polling table to store the RTT of every ONU.

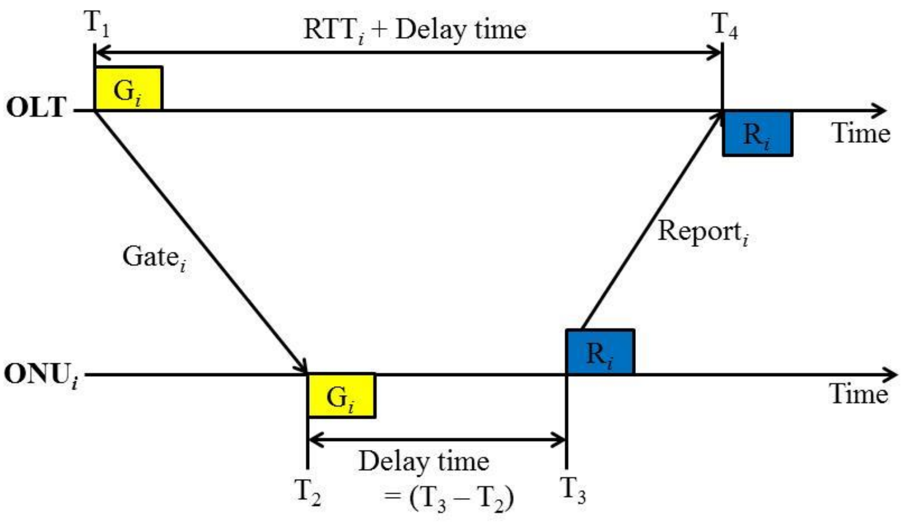


Fig. 2.3 RTT measurement in a PON.

Figure 2.3 shows a diagram of the RTT measurement in a PON system. The OLT first initiates the RTT measurement process by sending a Gate message to an ONU. Here, the Gate message G_i is sent to the ONU i at an absolute time T_1 and the ONU i receives the Gate message at a time instant T_2. After receiving the Gate message every ONU requires sometimes for identifying the MAC address and processing the Report message. At a time instant T_3 the ONU i transmits a Report message R_i that is accepted by the OLT at a time instant T_4. The following equation is used to calculate the RTT of the ONU i.

$$RTT_i = (T_4 - T_1) - (T_3 - T_2) \tag{2.1}$$

here, RTT_i is the RTT delay of the ONU i.

Several variants of the PON have been established in the modern communication technology, e.g., TDM-PON, Wavelength division multiplexing PON (WDM-PON), Gigabit PON (GPON), and next generation PON (NGPON).

2.1.1 Time Division Multiplexing PON (TDM-PON)

In the TDM-PON, a single upstream channel is shared by several ONUs in the network [23, 28]. The OLT is responsible for allocating the upstream bandwidth to the ONUs. However, the downstream transmission is broadcasting in nature. In the TDM-PON, a bandwidth allocation algorithm is required for efficient distribution of the single upstream channel. For perfect scheduling of data transmission from the different ONUs a polling algorithm is also required in addition to the bandwidth allocation algorithm. Usually, polling algorithm is a cycle based protocol, which used to avoid high traffic load, data collision, and limits the maximum transmission window for each ONU. A commonly used polling algorithm is the round-robin, which orders the data transmission from every ONU in a periodic way. To improve the network performance, interleaved polling with adaptive cycle time (IPACT) [17] is used. The interleaved polling algorithm can also have different policies, such as an interleaved polling algorithm with and without stop polling. In all the interleaved polling algorithms, the OLT contains a polling table which provides information about the RTT to the entire ONUs and their granted window sizes. Additionally, a guard time is used between every two successive ONUs to avoid overlapping of the transmission windows by fluctuations in the RTT calculation [29] and on/off timing of the lasers in both the OLT and ONUs.

2.1.2 Wavelength Division Multiplexing PON (WDM-PON)

Nowadays, the WDM-PON is considered as the most popular next generation access technology by many service providers. In the WDM-PON, several optical carriers are multiplexed together by using different wavelengths and then transmitted through a single optical fiber in both the directions, i.e., upstream and downstream, between the OLT and ONUs. There is no doubt that the TDM-PON is an excellent solution to overcome the problems associated with the copper-based access networks [30]. However, for providing further improvement in terms of bandwidth the WDM-PON has been proposed in the mid-1990s.

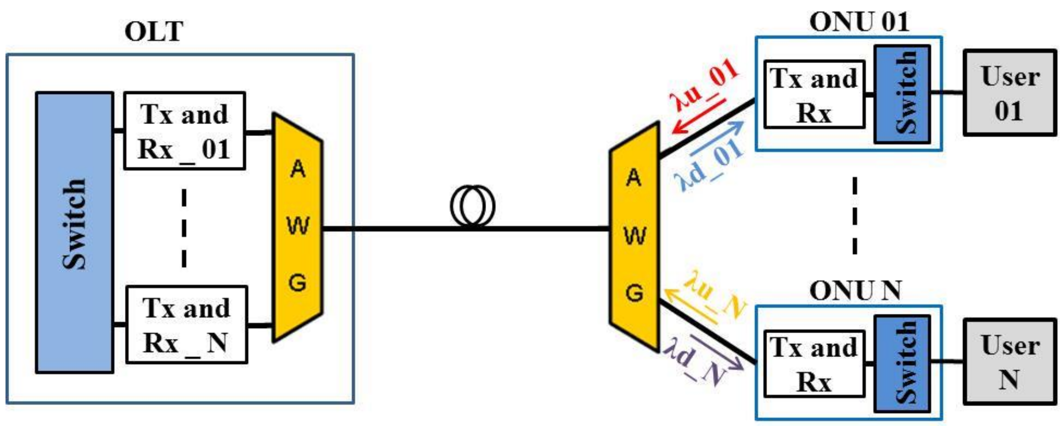


Fig. 2.4 WDM-PON architecture.

Figure 2.4 shows a typical architecture of a WDM-PON. In the downstream direction of the WDM-PON, several wavelengths are combined in an arrayed waveguide grating (AWG) placed in the OLT then another AWG is placed in the remote node (RN) that filters a specific wavelength and guided to a specific ONU through an optical fiber. Here, the OLT contains a multi-wavelength source for transmitting multiple wavelengths to different ONUs [30] where the number of wavelengths is equal to the number of ONUs in the network. In the upstream direction of the WDM-PON, the OLT receives different wavelengths from the different ONUs by using a receiver array and a WDM demultiplexer.

In the WDM-PON, a simplified MAC layer is used because it does not require any complicated DBA algorithm. However, a DBA algorithm has been proposed which is called WDM-PON DBA [31] for increasing throughput of the WDM-PON by finding an appropriate wavelength for each traffic. To implement this DBA in the WDM-PON, the MPCP of the TDM-PON is upgraded that assigns both the time slots and wavelengths [32].

2.1.3 Gigabit PON (GPON)

The international telecommunication union (ITU) has recommended G.984.x series for the GPON standard [33, 34, 35]. In this standard, several upstream and downstream data rates up to 2.48832 Gbps are specified [36]. The GPON provides high-speed and high-bandwidth for voice, data, and video services to both the residential and business subscribers. The GPON also provides a cost effective solution for the FTTH services [37, 38]. The GPON uses Ethernet frame fragmentation scheme to encapsulate the data packets and the Ethernet headers called general encapsulation method (GEM). The GEM transport layer supports asynchronous transfer mode (ATM), the Ethernet, and the TDM data transport. The GPON uses different status reporting mode to provide a simple and efficient means of setting up a system for multiple service classes [36]. The basic GPON systems support a maximum physical reach of 20km on a 32-way splits or 10km on a 64-way splits. However, fiber and optical amplifiers can be used to extend the reach of a GPON system with a 64-way splits to 60km [39].

In the downstream transmission of the GPON, the maximum data rate is 2.4 Gbps. That means the bandwidth for each optical network terminal (ONT) is sufficient to support the multiple HDTV signals. It provides a very high level of QoS support that is suitable for the delay sensitive traffics, e.g., voice traffic and real time video streaming.

In the upstream transmission of the GPON, the maximum data rate is 1.24 Gbps and the minimum bandwidth for each ONT can be guaranteed. The unused timeslots can be assigned to the heavily loaded users. The QoS is also allowed for the delay sensitive traffics.

2.1.4 Next Generation PON (NGPON)

In the NGPON both the EPON and the GPON systems are expected to be coexisted for the foreseeable future in the modern communication area [40]. To meet the ever increasing demands for high bandwidth requirements from the end users, the 10G EPON task force was formed, known as IEEE 802.3av [41]. However, the full service access network (FSAN), a standardization organization, has introduced the NGPON to achieve higher performance parameters, e.g., high bandwidth, increased split ratio, and extended maximum reach, than the existing EPON and GPON [42]. The NGPON is primarily divided into two phases, e.g., NGPON1 and NGPON2. The NGPON1 is a midterm upgradation of the typical PON system where its major requirements have been coexisted with that of the GPON and reuse of the outside plant. In contrast the NGPON2 is a long-term solution in the PON evolution. A most important requirement of the NGPON1 is to provide higher data transmission rates than the GPON. In addition, the operators expect that the NGPON1 will leverage the existing optical deployments. Hence, the FSAN and ITU Telecommunication (ITU-T) specified the NGPON1 backward compatibility with the existing GPON deployments to protect the initial GPON investments of the operators [43]. Table 2.1 shows comparisons among the GPON, WDM-PON, and NGPONs.

Table 2.1 Comparisons among WDM-PON, GPON, and NGPONs.

Quantity	WDM-PON	GPON	NGPON1	NGPON2
Standards	None	ITU G.984	FSAN	FSAN
Framing	Protocol Independent	GEM	GEM	GEM
Maximum Bandwidth	1-10 Gbps/channel	2.5Gbps 1.25Gbps	10Gbps 2.5Gbps	10Gbps
Users per PON	16-32	32-64	≥64	≥64
Cost	Very high	Medium	High	High

2.2 DBA Algorithms

DBA algorithms are playing a vital role in distributing the upstream bandwidth to the ONUs in the TDM-PON. Intensive researches have been conducted on the DBA algorithms over a PON [17,24,26,29,44,45,46,47,48,49,50,51,52] and among them, the popular schemes are the limited service (LS) [17], excessive bandwidth reallocation (EBR) [29], limited sharing with traffic prediction (LSTP) [51], and early DBA (E-DBA) [52] schemes.

2.2.1 Limited Service (LS) Scheme

In the LS scheme, the granted time slot length for an ONU depends on the dynamic network traffic and the maximum length of a transmission window is upper-bounded by the Ω^{max}. If the requested bandwidth Ω_i^R by the *i*th ONU is less than the Ω^{max} then the granted bandwidth from the OLT is equal to the Ω_i^R. In contrast, if the Ω_i^R is greater than or equal to the Ω^{max} then the granted bandwidth from the OLT is equal to the Ω^{max} . Equation 2.2 shows the bandwidth allocation formula for the LS scheme. This scheme mainly depends on the control messages, e.g., Gate and Report messages, defined by the MPCP [53] to track the traffic load of each ONU and to expedite the bandwidth negotiation.

$$\Omega_i^G = \begin{cases} \Omega_i^R & \text{if } \Omega_i^R \le \Omega^{max} \\ \Omega^{max} & \text{if } \Omega_i^R > \Omega^{max} \end{cases} \tag{2.2}$$

where Ω_i^G is the granted bandwidth to the ONU *i* by the OLT.

The main disadvantage of this scheme is that it does not consider the arriving data traffics during the waiting time, the time between the transmission of the Report message from an ONU and the reception of the Gate message from the OLT. That is why, this scheme is not suitable for the delay and jitter sensitive services because of the variable length of polling cycle.

2.2.2 Excessive Bandwidth Reallocation (EBR) Scheme

This scheme proposed to divide the total ONUs in a network into two groups depending on the accumulated data packets in the queue of an ONU called heavily loaded ONUs and lightly loaded ONUs. One of the main objectives of this scheme is to avoid the light-load penalty. This algorithm also supports differentiated services by employing a suitable intra-ONU priority scheduling scheme. This scheme provides better bandwidth utilization by utilizing the excessive bandwidth from the lightly loaded ONUs to the heavily loaded ONUs.

Priority queuing is a useful and simple method for supporting the differentiating service classes [27]. In this scheme, each ONU maintains three different priority queues with same buffering space. First, the incoming packets are classified and placed in their appropriate priority queues. According to the rule of this scheme, if a packet arrives with the higher priority but finds that the high priority buffer is already full, then it stores at a lower priority queue. In contrast, if a lower priority packet arrives and the lower priority queue is full, then the packet is dropped. Three priority groups are specified as high-priority H_i, medium-priority M_i, and low-priority L_i and the ONU can transmit the bandwidth request for every priority group individually by using the MPCP Report messages. Note that the MPCP can reports up to eight priority queues [14,54]. On the other hand, the OLT generates three different Gate messages to respond to the Report messages of the three traffic classes as H_i^G, M_i^G, L_i^G, respectively.

2.2.3 Limited Sharing with Traffic Prediction (LSTP) Scheme

The LSTP scheme supports dynamic bandwidth negotiation between the OLT and ONUs. The end-to-end packet delay is reduced by predicting the deferred traffic that arrives during the waiting time between the transmission of the Report message from an ONU and the reception of a Gate message from the OLT. This scheme also provides an option to preserve some bandwidth for delivering the data packets during the waiting time.

The bandwidth negotiation between the OLT and the ONUs is held by employing the control messages in the MPCP. Usually, in both the LS and EBR schemes each ONU transmits a Report message containing a requested bandwidth size for the next time cycle according to the present buffer size. However, in the LSTP scheme, the Report message from each ONU contains the predicted data size that arrived during the waiting time in addition to the present buffer size.

The bandwidth prediction for an ONU during the waiting time depends on the rate of actual accumulated traffics in the queue before transmitting the Report message. This prediction depends on the characteristics of the self-similar network traffic [55].

In the LSTP scheme, the bandwidth prediction during the waiting time can provides the advantages of low computational complexity, fast convergence, and no prior knowledge of the traffic statistics, the linear predictor (LP) is considered as a practical device to conduct the online traffic prediction [56,57].

2.2.4 Early DBA (E-DBA) Scheme

The E-DBA scheme reduces the idle period in the usual DBA scheme by analyzing the historical traffic management. The E-DBA sorts the sequence of each ONU according to the variance in historical traffic required and arranges some Report messages from the ONUs. To improve the system performance and fairness of excessive bandwidth allocation among the ONUs the E-DBA scheme is incorporated with the prediction-based fair excessive bandwidth allocation (PFEBA) scheme. The PFEBA scheme provides more accurate prediction to ensure the fairness and that is not only for the heavily loaded ONUs but also for the lightly loaded ONUs. The PFEBA scheme works in three steps. In the first step it prepares an unstable degree list by using the historical traffic analysis then the prediction is made according to the unstable degree list. Finally, the fair excessive bandwidth allocation scheme is implemented.

The E-DBA scheme provides reduction of packet delay by early execution of DBA mechanism and reduction of an idle period. In this scheme, the bandwidth is allocated to each ONU according to the decreasing order of the unstable degree list. Usually, the idle period that considered in this scheme is the sum of the computation time for a DBA scheme and the RTT. System performance and bandwidth utilization of a PON can be improved by reducing this idle period.

2.3 Conclusions

In this chapter, several conventional PONs and DBA algorithms have been explained in brief. From the survey on the existing PONs, it is found that all the network structures and developments of PONs are based on the FTTH-based network traffics. Every PON system has been proposed to provide some better performances and QoSs. For achieving better QoSs, all the PONs require a little bit more complex network structures or higher expenses. For example, the NGPON or GPON provides better performance than the basic TDM PON in terms of higher bandwidth and throughput. On the other hand, the WDM PON provides higher bandwidth and throughput with lower complexity than the basic TDM PON. However, the NGPON or GPON requires more complexity while the WDM PON requires more expenses than the TDM PON. This thesis has investigated the necessity of connecting several service providers in a u-City through a single PON-based access network to reduce the network deployment cost for several servide providers which is never considered in all the above PON systems. All the existing PON systems only consider a single service provider.

Concerning the DBA algorithms, it is found that all the DBA schemes also have been considered only for the FTTH-based network traffics. There is no DBA algorithm for a hybrid network. All the DBA schemes have provided a very little medication to the LS scheme to provide improvement of one or more specific parameters, e.g., delay, bandwidth utilization, throughput, and jitter. However, in the hybrid networks, different service providers have different maximum packet lengths and data rates. That is why, alike all the DBA schemes using a single maximum transmission window in the hybrid networks is not an effective approach in terms of improving the bandwidth sharing efficiency among the multiple service providers. This thesis has investigated all those technical constraints in the existing DBA schemes for designing a new DBA algorithm for the proposed hybrid PON. In the near future, emerging from the work on the single-channel PONs, researchers are beginning to extend the DBA problem to PONs that employ more than one upstream and/or downstream channels [58,59,60,61]. The DBA algorithms for the multi-wavelength PONs represent an extensive area for the future researchers.

In this thesis, several new network structures and DBA algorithms have been proposed for the PON-based hybrid FTTH and WSNs. The main objective of this hybrid network is to comprise two different service providers with their own features in a single PON. Moreover, the new DBA algorithms provide enhanced performances than the conventional DBA algorithms by employing individual maximum transmission windows for every service provider depending on their maximum length of data packets. These new DBA algorithms are very effective to improve the bandwidth sharing efficiency among the multiple service providers in a single hybrid network.

3. Architectures of PON-Based Hybrid Networks

This chapter presents two new network architectures of the proposed PON-based hybrid networks comprising the FTTH and WSNs. The presentation consists of a single-OLT PON-based hybrid network and a multi-OLT PON-based hybrid network. In addition to the network architectures, this chapter also enlightens about the MPCP, Guard time management, and Gate message scheduling algorithm of both the single-OLT and multi-OLT PON-based hybrid networks.

3.1 Single-OLT PON-Based FTTH and WSNs

These days, the number of different service providers, e.g., FTTH, WSNs, LAN, FNs, and ad-hoc networks, in a u-City has increased dramatically. Most of the service providers are providing their services by using individual network. Some service providers are using wireless networks and rests of them are using fiber based networks. It's a demand of modern time to provide an interlink between the wireless and fiber-based networks. Moreover, providing an effective interlink among those service providers through a common backbone network will enhance the beauty of the modern communication technology. In this context, the PON-based access networks can be a very good candidate to provide the required bandwidth demands of the converged hybrid networks of several service providers. Furthermore, sharing a PON between two different service providers, i.e., CHs of a WSNs and FTTH terminals, through a common optical fiber link can provide a cost-effective and flexible infrastructure that can effectively reduces the cost of physically deploying the individual optical fiber networks for every service provider.

In this section, a tree topology-based hybrid PON architecture is considered that comprises an OLT, a splitter/combiner, and several ONUs. In the following explanation, a network architecture of a single-OLT PON-based hybrid network is shown where the 50% ONUs are connected to the CHs of a WSN and the rest of the 50% ONUs are connected to the FTTH terminals for simplicity. However, the ratio of the number of ONUs connected to the CHs of WSN and the FTTH terminals can be changed.

3.1.1 Network Architecture of a Single-OLT PON-Based FTTH and WSNs

This subsection explains the proposed network structure of a single-OLT PON-based hybrid networks combining the FTTH access networks and the WSNs. Figure 3.1 shows the proposed network architecture. This is a tree topology-based hybrid PON consists of one OLT located on the tree side with both the FTTH and WSN service providers connected to the several ONUs on the leaf side of the network. The OLT is connected to the several ONUs through optical fiber links using a 1:*N* optical splitter/combiner. Most of the PON systems consist of one OLT and *N* ONUs connected to the FTTH terminals with different RTT delays. In contrast, the proposed hybrid PON structure consists of ONUs from two different operators, i.e., ONUs connected to the FTTH terminals and ONUs connected to the CHs of a WSN. The number of ONUs connected to the FTTH terminals and the number of ONUs connected to the CHs of the WSN may vary; however, for simplicity, only four ONUs for both the services with the different RTTs are shown in the Fig. 3.1.

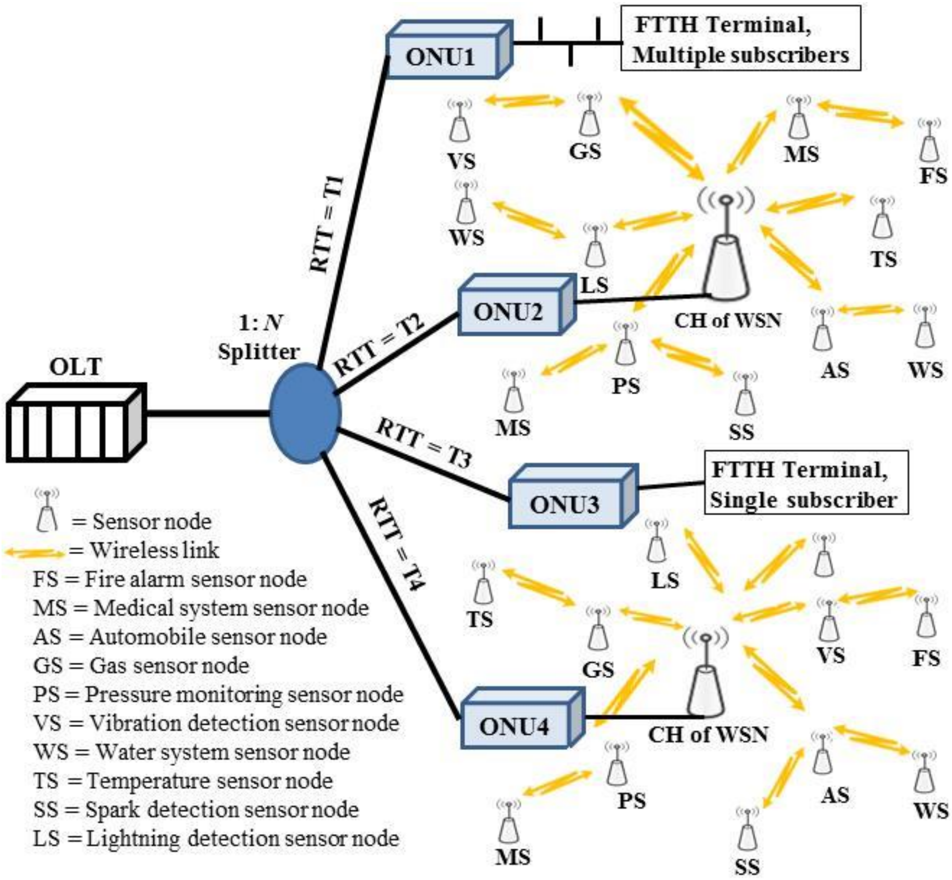


Fig. 3.1 Network architecture of a single-OLT hybrid PON with 2 ONUs connected to the FTTH terminals and 2 ONUs connected to the CHs of a WSN.

3.1.2 MPCP for a Single-OLT Hybrid PON

The MPCP [14, 27] is an important protocol in the MAC layer of the PON system to avoid data collisions and sharing of the single optical fiber link with the multiple ONUs in a tree-based PON topology. In the downstream transmission, the Gate message and the downstream data packets are broadcasted from the OLT to all the ONUs in the network. Each ONU accepts data packets from the OLT according to the destination address. The main information contained in a downstream packet is the upstream transmission time and the length of the transmission window of each ONU. In the upstream transmission, only a single ONU can transmit the upstream data in a specified time-slot to avoid data collisions and packet loss. The upstream transmission window of each ONU also contains a Report message at the end of a time-slot to request the desired window size for the next time cycle in accordance with the ONU's buffer occupancy.

Figure 3.2 shows an illustrative example of the MPCP in a single-OLT PON using an OLT communicating with an ONU. Here, the ONU sends the bandwidth request for the next time cycle by a Report message and the OLT approves the ONU's request by the Gate message with the granted window size after referring the DBA scheme. As soon as the Gate message is received the ONU tramsmits the upstream data from its FIFO buffer.

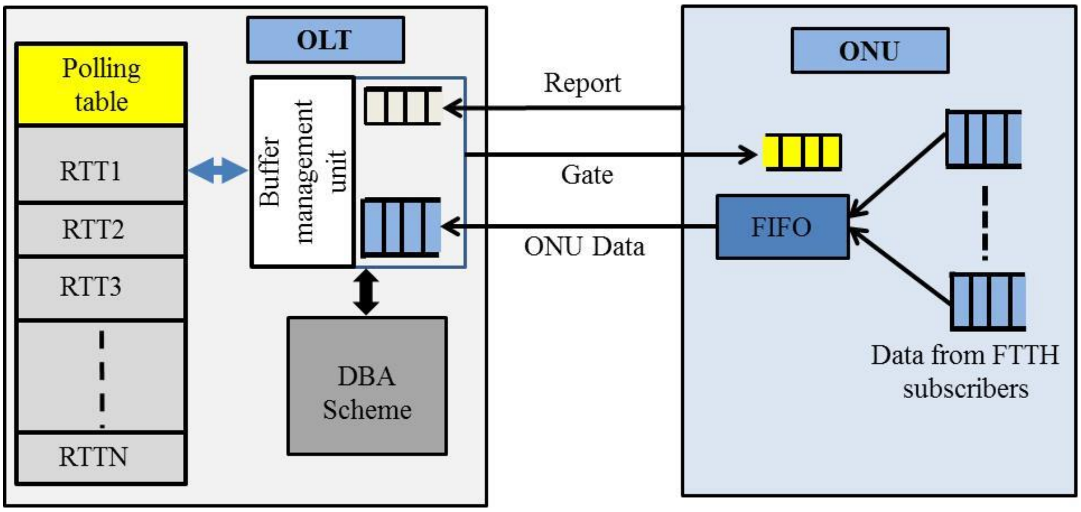


Fig. 3.2 MPCP operation in a single-OLT PON.

3.1.3 Guard Time Management in a Single-OLT Hybrid PON

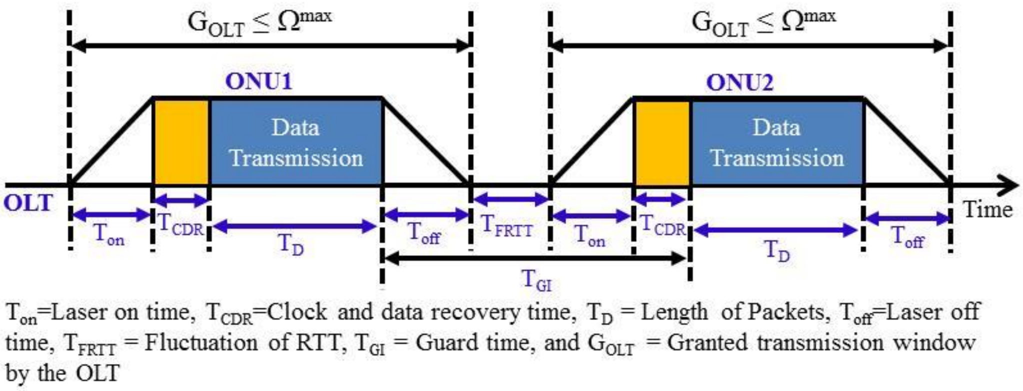


Fig. 3.3 Guard time management in a single-OLT PON.

In a PON system, guard time is required to avoid the turn on/off delay of an optical transceiver, fluctuation of the RTT (FRTT), and to provide time for clock and data recovery (CDR). A typical

PON system has to cope with these constraints by providing enough space as a guard time between the transmission windows of every two consecutive ONUs. Figure 3.3 illustrates the guard time management in a conventional single-OLT PON system. This figure is an example of the guard time management in a single-OLT PON using two ONUs with the Ω^{max} for every ONU, and fluctuation of the RTT T_{FRTT}.

The guard time T_{GI} between every two consecutive ONUs in the single-OLT PON is explained by the following equation.

$$T_{GI} = T_{off} + T_{FRTT} + T_{on} + T_{CDR} \tag{3.1}$$

where, T_{off} is the laser off time, T_{on} is the laser on time, and T_{CDR} is the time for clock and data recovery.

In a conventional PON, the Ω^{max} is a constant for each ONU. The maximum granted transmission window to each ONU by the OLT, G_{OLT}, can be calculated as follows:

$$G_{OLT} = \Omega^{max} = T_{on} + T_{CDR} + T_D^{max} + T_{off} \tag{3.2}$$

where, T_D^{max} is the length of the maximum granted data packets.

3.1.4 Gate Message Scheduling Algorithm in a Single-OLT Hybrid PON

In the OLT of a single-OLT PON, the individual Gate message is generated for every ONU. Usually, the order of the Gate messages is different from the order of the Report messages. The Report message from each ONU arrives in the same order in every time cycle. Scheduling sequences of the Gate messages depend on the RTT delays from the OLT to ONUs. As a result the order of the Gate messages may be different with the order of the ONUs, e.g., the Gate massage of the ONU *i* can be sent before the Gate message of the ONU *i*-1.

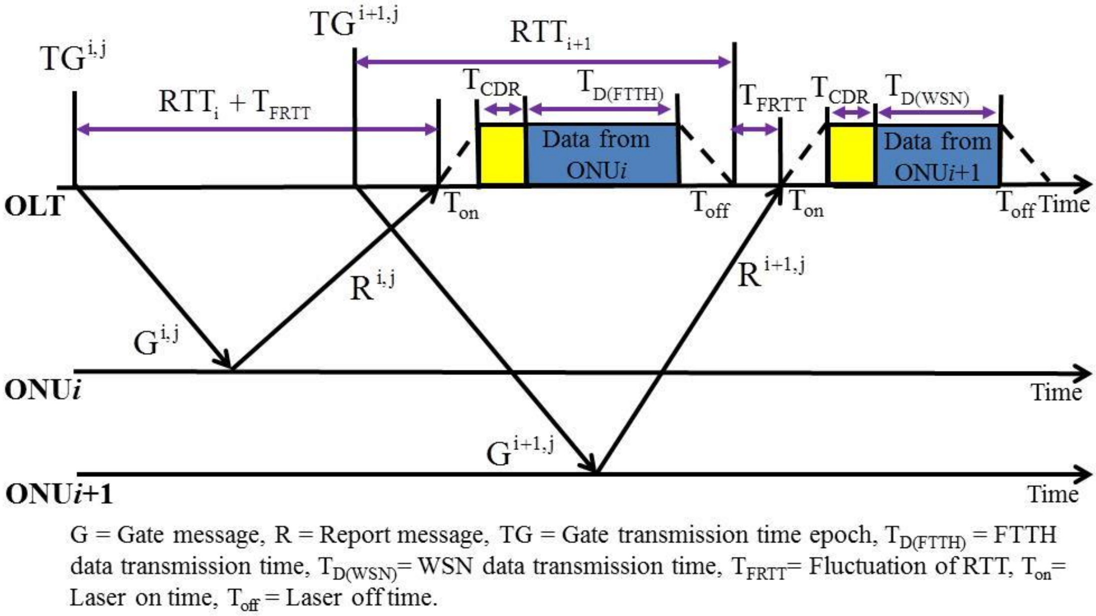


Fig. 3.4 Scheduling diagram of the Gate messages in a single-OLT PON.

Figure 3.4 shows the scheduling diagram of the Gate messages for a single-OLT PON. Here, the figure shows that the 1st Gate is scheduled to the ONU *i* and the 2nd Gate is scheduled to the ONU *i*+1. However, the 1st Gate should be scheduled to the ONU *i*+1 if the RTT of the ONU *i*+1 is greater than the RTT of the ONU *i*. On the other hand, the interval between the two consecutive Gate messages to the same ONU is at least the RTT delay to that ONU [62].

Following formula is used to schedule a Gate message in a single-OLT PON:

$$TG^{i+1,j} = TG^{i,j} + (RTT_i + T_{FRTT}) + T_{on} + T_{CDR} + T_{D(FTTH)} + T_{off} - RTT_{i+1} \tag{3.3}$$

where, $TG^{i,j}$ is the time epoch when the *j*th Gate to the *i*th ONU is transmitted, $TG^{i+1,j}$ is the time epoch when the *j*th Gate to the (*i*+1)th ONU is transmitted, RTT_i is the round trip time for the ONU *i*, RTT_{i+1} is the round trip time for the ONU *i*+1, $T_{D(FTTH)}$ is the data transmission time of ONU *i* connected to the FTTH terminal, $T_{D(WSN)}$ is the data transmission time of ONU *i*+1 connected to the CH of a WSN, T_{on} is the laser on time, T_{CDR} is the clock and data recovery time, and T_{off} is the laser off time.

3.2 Multi-OLT PON-Based FTTH and WSNs

In a modern u-City, constructing a common network for multiple service providers in a single-OLT PON requires more computational complexity for data packet processing in the OLT. Because the multiple service providers in a u-City have their own features which are different than each other. That is why, the present network structures are not that much effective to provide a common interlink among all the service providers in the u-City. However, a PON is an excellent technology that can provide enough bandwidth for the multiple service providers in the hybrid networks because the PON systems can effectively share the upstream channel and the CO equipments over high-speed and high-capacity bandwidth demands [63]. But the current PON is not that much effective to share the data from the multiple service providers as its present form. The main reason is that the single OLT will suffer from huge burden of data processing for the data of different service providers having different packet sizes and data rates. The only possible solutions to overcome this burden in the single-OLT PON is providing larger guard intervals and more processing times but it will reduce the bandwidth utilization and increase the packet delay and data congestion. A multi-OLT PON-based hybrid network can be a good alternative than the existing single-OLT PON for combining several service providers in a u-City as the multiple OLTs can share the processing times of data packets from the different service providers. As a result the larger guard intervals and more processing times will not be required.

This thesis proposes a multi-OLT PON-based hybrid network combining the FTTH access terminals and WSNs in a single PON. Even though, the single-OLT PON-based hybrid networks, as explained in the previous section of this thesis, can be used to connect the multiple service providers in a u-City using additional processing times and the larger guard intervals alike the OANs, but a Multi-OLT PON can play a dynamic role to alleviate the ascended problems in a single-OLT PON during the management and computing of the data packets from the multiple service providers with less overhead in the upstream channel. In a multi-OLT PON, each OLT independently handles the control messages and data packets of each service provider in a u-City.

In this section, the proposed network architecture of the hybrid multi-OLT PON combining the FTTH terminals and WSNs is explained with the modified version of the MPCP, proper guard time management, and Gate scheduling algorithm suitable for the hybrid multi-OLT PON.

3.2.1 Network Architecture of a Multi-OLT PON-Based FTTH and WSNs

One of the main aspects of the PON architecture that helped it to become a popular network is its simplicity. The OLT is the main element of the network and is usually placed in the CO. The ONUs serve as an interface between the OLT and the users through a splitter/combiner and an optical fiber link. This section explains a tree-topology-based hybrid multi-OLT PON consists of multiple OLTs that are connected to the several ONUs of the FTTH and WSNs service providers. In the multi-OLT PON, a cluster-based WSN is considered where each cluster consists of a static CH connected to an ONU through an optical fiber [13]. It is usual that a PON system consists of one OLT and N ONUs and the entire ONUs are connected to the FTTH terminals. However, the proposed hybrid multi-OLT PON structure consists of multiple OLTs and several ONUs from two different service providers connected to FTTH terminals and CHs of a WSN. In the multi-OLT PON, the number of OLTs depends on the practical scenario, the number of service providers installed, in a u-City. If a u-City comprises m different service providers then the number of OLTs will be m, e.g., OLT1 for FTTH terminals, OLT2 for WSNs, OLT3 for HDTV/VoD, …. and OLT m for FNs. Therefore, the number of OLTs and ONUs in the network may vary; however, for simplicity, only two OLTs with a shared polling table and four ONUs connected to the two service providers with both the upstream and downstream packets are shown in Fig. 3.5. Here, the ONU1 and ONU3 are connected to the users1 and user2 of the FTTH network while the ONU2 and ONU4 are connected to the CH1 and CH2 of the WSN. The single splitter can be divided into two and a longer feeder optical fiber can be installed between them, although it is not shown in the Fig. 3.5.

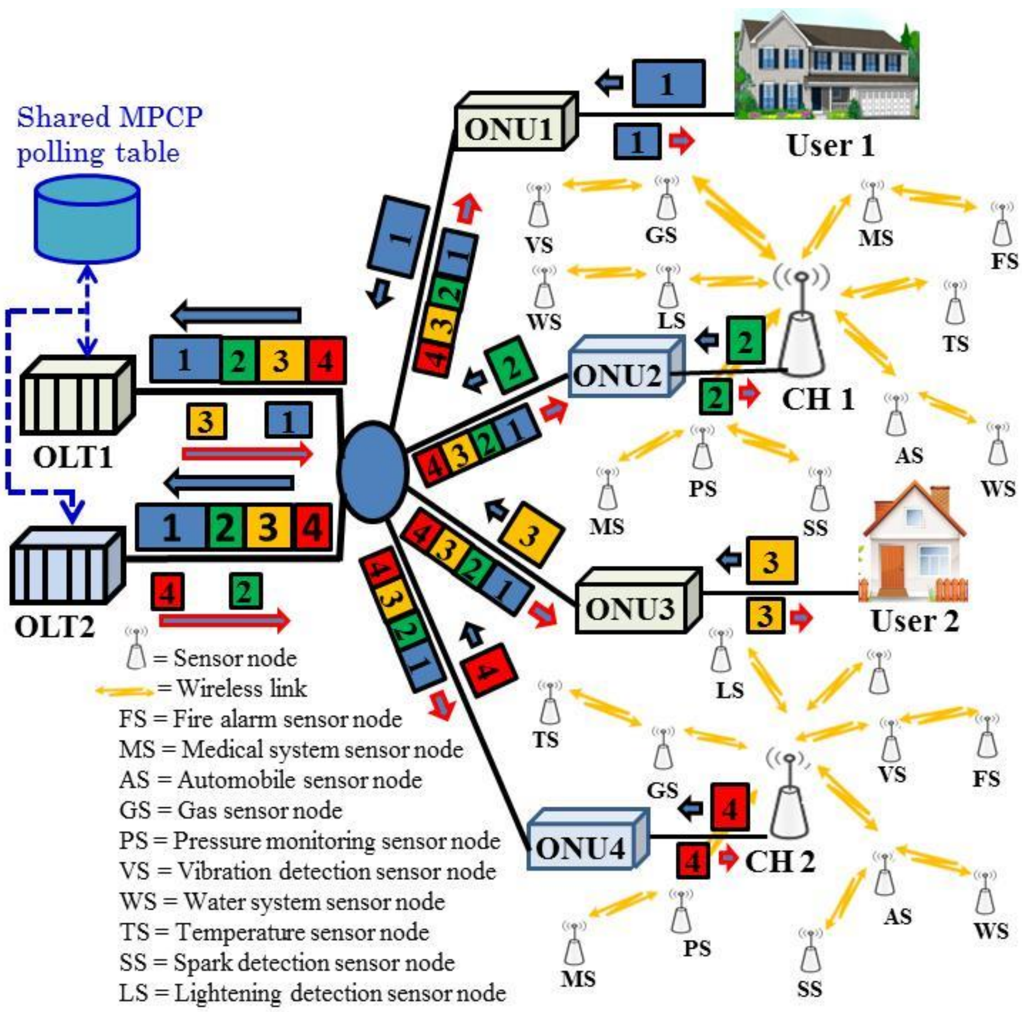


Fig. 3.5 Network structure and data transmission for a hybrid multi-OLT PON.

In the downstream direction of the multi-OLT PON, each OLT alternately broadcasts data to the network through a passive splitter. All the ONUs receives the broadcasted data from both the OLTs but each ONU selectively extracts the data packets from the OLT of the corresponding service provider.

In the upstream direction of the multi-OLT PON, data packets from any ONU will reach to both of the OLTs. However, data packets from an ONU will be accepted only by the designated OLT. Other OLTs will discard the data packets from that ONU and will wait for the data packets from the next ONU.

3.2.2 MPCP for a Multi-OLT Hybrid PON

The MPCP provides timing reference to synchronize ONUs and allocate transmission windows or timeslots to the ONUs to allow efficient transmission of data in the upstream direction. In the MPCP, timing synchronization among the ONUs is achieved by calculating the RTT and by maintaining a polling table. The MPCP uses a DBA algorithm to allocate the transmission window or timeslots for every ONU and to share the single optical fiber link with the multiple ONUs [64].

In the downstream transmission of the hybrid multi-OLT PON, the MPCP maintains a timestamp with its local time and broadcasts a Gate message to all the ONUs. In the upstream transmission of the hybrid multi-OLT PON, all the ONUs share a common channel to transmit data to the OLTs. The upstream transmission window of each ONU also contains a Report message at the end of its timeslots to request the desired transmission window in the next time cycle depending on the ONU's buffer occupancy. Upon receiving the Report message at the OLT, the MPCP incorporated with the

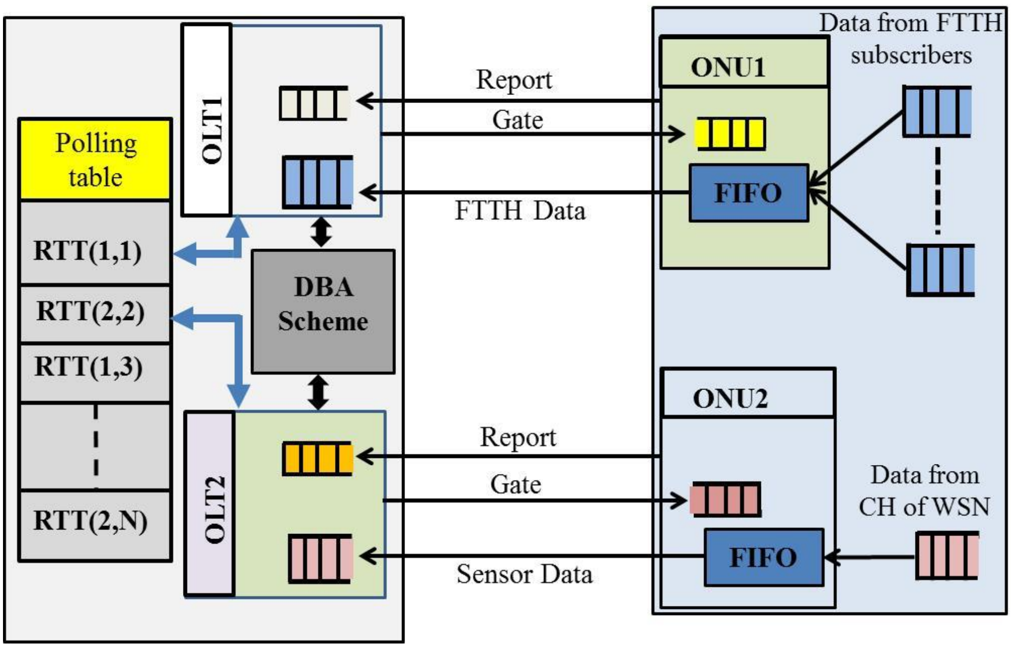


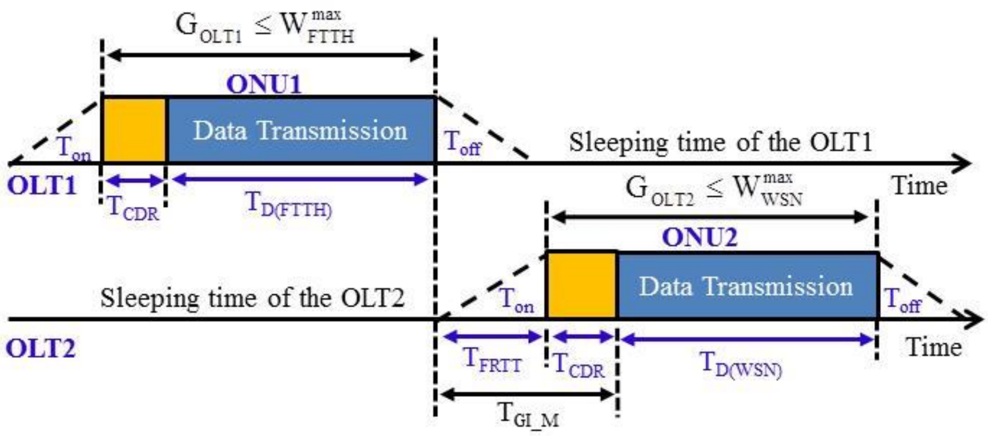
Fig. 3.6 MPCP operation in a hybrid multi-OLT PON.

DBA algorithm determines the allocated transmission window and recalculates the required overhead and the RTT to update the polling table. In a multi-OLT PON, the conventional MPCP is modified, where both the OLTs share a common polling table to store the RTT of each ONU that ensures the timing synchronization among all the ONUs.

Figure 3.6 illustrates an example of the MPCP operation for the proposed hybrid multi-OLT PON with two OLTs and two ONUs connected to the two service providers. The ONU1 sends the 1st Report message to the OLT1 and the ONU2 sends the 2nd Report message to the OLT2. Both the OLTs collect the RTT information from the shared polling table and consult with the DBA scheme then send the Gate messages to both the ONUs. The time sequence for sending the Gate messages from both the OLTs depends on the RTT of both the ONUs.

3.2.3 Guard Time Management in a Multi-OLT Hybrid PON

In a multi-OLT PON, two OLTs alternately receive data packets from the two consecutive ONUs, and both the laser on time T_{on} and the laser off time T_{off} can be easily avoided. When the data of the ONU1 are received by the OLT1, the OLT2 is in a sleeping condition at that time and can wake up early to provide enough time for the T_{on} and receive data during the T_{off} of the OLT1. In contrast, when the data of the ONU2 are received by the OLT2, the OLT1 is in a sleeping condition at that time and can wake up early to compensate for the T_{on} and receives data during the T_{off} of the OLT2.



$T_{D(FTTH/WSN)}$ = Length of packets from FTTH terminal or WSN, T_{GI_M} = Guard time in multi-OLT PON, and $G_{OLT1/2}$ = Granted transmission window by OLT1/OLT2

Fig. 3.7 Guard time management in a multi-OLT PON.

Figure 3.7 shows the guard time management in a multi-OLT PON system where only the CDR and RTT fluctuation times are used as the guard time. In Eq. 3.4, T_{GI_M} is the guard time between every two consecutive ONUs in a multi-OLT PON.

$$T_{GI\_M} = T_{FRTT} + T_{CDR} \tag{3.4}$$

The total guard time savings T_{GI_TS} in every time cycle in a multi-OLT PON can be calculated as follows:

$$T_{GI\_TS} = N(T_{GI} - T_{GI\_M}) = N(T_{on} + T_{off}) \tag{3.5}$$

where, T_{GI} is the guard time in the single-OLT PON calculated in the Eq. 3.1, and N is the number of ONUs.

In a multi-OLT PON, the maximum transmission window for each ONU connected to the FTTH terminal is $W_{FTTH}^{\max}$ while the maximum transmission window for each ONU connected to the CH of a WSN is $W_{WSN}^{\max}$. The maximum granted transmission windows to the ONUs of the FTTH terminals and WSN by the OLT1 and OLT2 can be expressed by Eqs. 3.6 and 3.7, respectively:

$$G_{OLT1} = W_{FTTH}^{\max} = T_{CDR} + T_{D(FTTH)}^{\max} \tag{3.6}$$

$$G_{OLT2} = W_{WSN}^{\max} = T_{CDR} + T_{D(WSN)}^{\max} \tag{3.7}$$

where, G_{OLT1} is the granted window by the OLT1, G_{OLT2} is the granted window by the OLT2, $T_{D(FTTH)}^{\max}$ is the length of the maximum granted data packets to the ONUs of the FTTH terminal, and $T_{D(WSN)}^{\max}$ is the length of the maximum granted data packets to the ONUs of the WSN.

3.2.4 Interleaved Polling Algorithm in a Multi-OLT Hybrid PON

The transmission time and propagation delay of data packets in the PON system depend on the transmission speed and physical distance between the OLT and ONUs. Usually, the physical distances between an OLT and ONUs are not equal [14] but the data transmission speed is a constant for the TDM PON. In the TDM PON, the OLT broadcasts the downstream traffic but the upstream traffics from each ONU is allowed at a particular transmission time [36]. To cope with these features of the PON several polling algorithms have been developed.

The main aspect of a polling algorithm is the scheduling of data transmission of the ONUs in a network. Usually, the polling algorithm is a cycle based protocol, which is used to avoid the high traffic load in a time cycle as well as data collision, and it limits the maximum transmission window for each ONU. The round-robin based polling is a commonly used polling algorithm in the PON, which orders the transmission of data packets from every ONU in a periodic way. To improve the performance of the TDM PON the IPACT [17] is the most effective polling algorithm. The interleaved polling algorithm can also have different policies, such as an interleaved polling algorithm with and without stop polling. In all the interleaved polling algorithms, the OLT contains a polling table which provides information about the RTT to every ONU and their granted window sizes. The polling algorithms help to avoid the overlapping of data transmission from the multiple ONUs. Additionally, a guard time is used between every two successive ONUs to avoid overlapping of transmission windows by fluctuations in the RTT of different ONUs [29] and the on/off timing of the lasers in both the OLT and ONUs. Without using this guard time a single-OLT PON cannot ensure the overlap free transmission between the two consecutive ONUs.

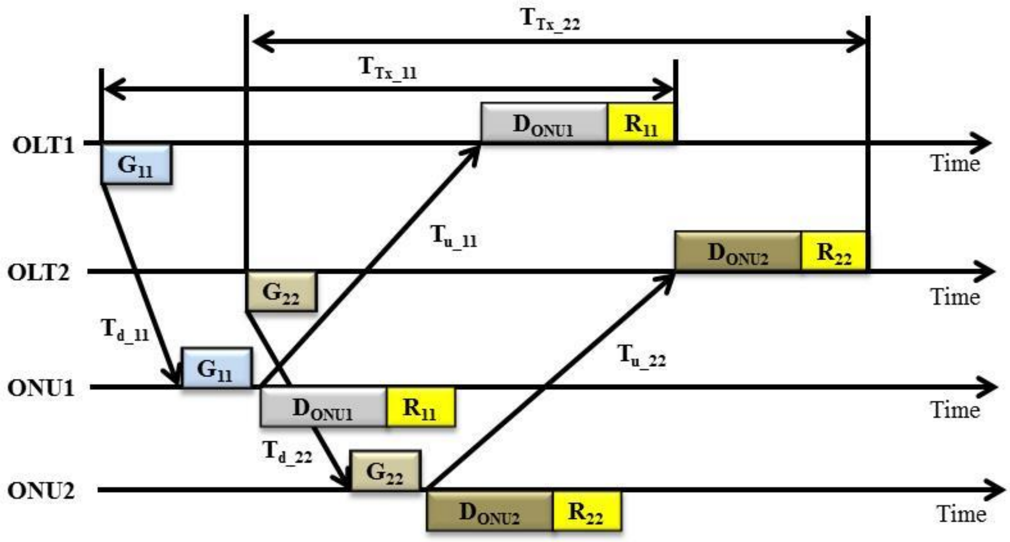


Fig. 3.8 RTT and data transmission time in a multi-OLT PON.

In the multi-OLT PON, the downstream and upstream transmissions from the multiple OLTs and ONUs must be well scheduled to improve the network performance and to avoid the data collisions. A modified version of the IPACT [17] is used for the proposed multi-OLT PON system, where a common polling table is considered for all the OLTs. Figure 3.8 shows the modified interleaved polling algorithm and the RTT calculation procedure for the proposed multi-OLT PON system. For simplicity, two different service providers, i.e., FTTH and WSN, and two OLTs are considered in this figure where ONU 1, 3, 5, … 2*i*-1 are for the FTTH terminals and those are connected with the OLT1. In contrast, ONU 2, 4, 6, … 2*i* are for the CHs of WSN and those are connected with the OLT2, here, *i* is an integer.

Equations 3.8 and 3.9 represent the principle of the RTT calculation in the multi-OLT PON-based hybrid networks, and Eqs. 3.10 and 3.11 represent data transmission times T_{Tx_11} and T_{Tx_22} for the OLT1 and OLT2, respectively.

$$T_{RTT\_11} = T_{d\_11} + T_{u\_11} \tag{3.8}$$

$$T_{RTT\_22} = T_{d\_22} + T_{u\_22} \tag{3.9}$$

$$T_{Tx\_11} = T_{Tx\_G_{11}} + T_{d\_11} + \frac{D_{ONU1}}{R_U} + T_{u\_11} + T_{Tx\_R11} \tag{3.10}$$

$$T_{Tx\_22} = T_{Tx\_G22} + T_{d\_22} + \frac{D_{ONU2}}{R_U} + T_{u\_22} + T_{Tx\_R22} \tag{3.11}$$

where, T_{Tx_G} is the transmission time of the Gate message, T_{Tx_R} is the transmission time of the Report message, T_d is the downstream propagation delay, D_{ONU} is the length of the upstream data packets, R_U is the data rate, and T_u is the upstream propagation delay.

3.2.5 Gate Message Scheduling Algorithm in a Multi-OLT Hybrid PON

In the upstream transmission of a multi-OLT PON, a scheduling algorithm for the Gate messages is very important to prevent data collisions due to the multiple ONUs transmitting at the same time. As the scheduling of the Gate messages depends on the RTT and granted window sizes of the different ONUs. In the multi-OLT PON, a starting Gate message can be sent by any of the OLTs. Figure 3.9 shows the Gate message scheduling algorithm in a multi-OLT PON. This figure represents just an example of the Gate message scheduling in a multi-OLT PON. Usually, the FRTT is not mandatory for every ONU at every time cycle. The FRTT may occurs randomly in different time cycles. However, two different FRTTs are considered for both the ONU *i* and ONU *i*+1 in the Fig. 3.9.

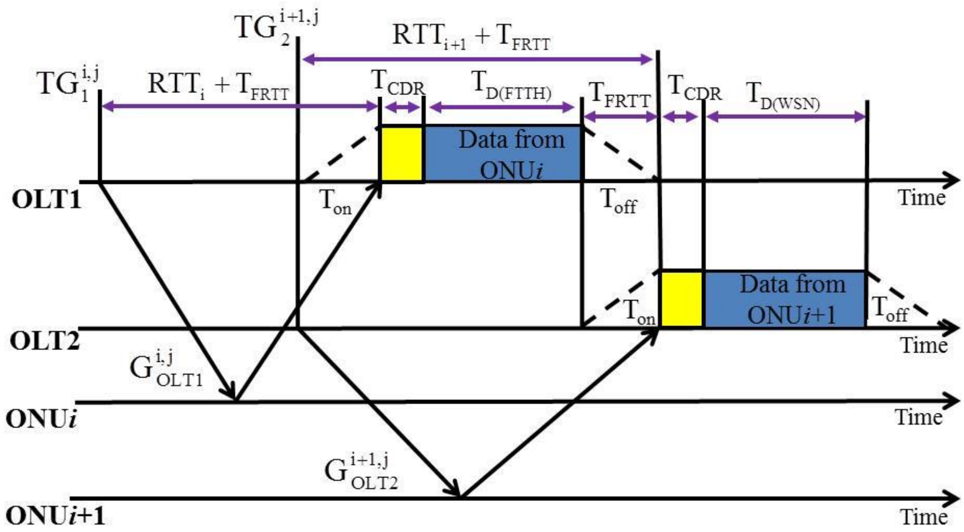


Fig. 3.9 Scheduling diagram for a Gate message in a multi-OLT PON.

The Gate messages for different ONUs in a multi-OLT PON are scheduled using the following formulas:

$$TG_2^{i+1,j} = TG_1^{i,j} + (RTT_i + T_{FRTT}) + T_{CDR} + T_{D(FTTH)} + T_{FRTT} - (RTT_{i+1} + T_{FRTT}) \quad (3.12)$$

$$TG_1^{i+2,j} = TG_2^{i+1,j} + (RTT_{i+1} + T_{FRTT}) + T_{CDR} + T_{D(WSN)} + T_{FRTT} - (RTT_{i+2} + T_{FRTT}) \quad (3.13)$$

where, $TG_1^{i,j}$ and $TG_2^{i+1,j}$ are the time epochs for the OLT1 and OLT2 when the Gate messages are transmitted to the ONU *i* and ONU *i*+1, respectively, at the time cycle *j*, and $TG_1^{i+2,j}$ is the time epoch for the OLT1 when the Gate message is transmitted to the ONU *i*+2 at the time cycle *j*.

3.3 Conclusions

In this chapter, two different architectures for the proposed PON-based hybrid networks combinig the FTTH and WSNs have been presented. These proposed PON-based hybrid network architectures significantly reduce the installation cost of individual network deployment for every service provider. Moreover, the huge bandwidth of a single optical fiber backbone network is capable to support the accumulated network traffics from the multiple service providers.

In the single-OLT PON-based hybrid FTTH and WSNs, two different service providers are comprised in a single optical network where the typical single-OLT PON is considered. The main drawback of this scheme is higher computational complexity for processing of data packets of the different service providers in a single OLT. However, this scheme reduces the requirement of additional expenses for deployment of new networks for the different service providers.

In the multi-OLT PON-based hybrid FTTH and WSNs, both the installation cost of new network deployment and the computational complexity of data packet processing for the different service providers have been mitigated. Moreover, both the data processing times and guard intervals also can be avoided by overlapping the processing times among the multiple OLTs. In addition to the above advantages, the main draw back of this multi-OLT PON is its shared polling table that restricts the installation of the multiple OLTs in different places.

4. DBA Algorithms for the PON-Based Hybrid Networks

For getting the optimum performance and QoSs from a network both of the effective network architecture and an efficient DBA algorithm suitable for that network architecture are required. This chapter presents several new DBA algorithms for the proposed two different hybrid network architectures of PON for improving the bandwidth sharing efficiency among the multiple service providers having different packet sizes and data rates.

4.1 Adaptive Limited DBA (ALDBA) Algorithms for the Single-OLT Hybrid PON

According to the TDM PON principles, only a single ONU can transmit data in a specified time-slot to avoid the data collisions and packet loss. The upstream transmission window of each ONU also contains a Report message at the end of a time-slot to request for the desired window size of the next time cycle depending on the ONU's present buffer. That is why, a robust bandwidth sharing algorithm is required to allocate the time-slot among the ONUs in the upstream direction. Different DBA algorithms have been proposed by several researchers. Among them, IPACT [17] is the most popular approach. In the IPACT, an OLT-based polling scheme is used to poll the next ONU before the data packets from the previous ONU has arrived. With this algorithm, all the traffic is assumed to be single class, i.e., service differentiation is not considered. G. Kramer et al. have studied the priority scheduling principle and combined it with the DBA algorithm to provide an effective service for the delay and jitter sensitive applications [24]. More recently, C. Assi et al. have proposed a new DBA algorithm with the QoS support that is combined with the priority scheduling and queue management schemes [29]. In this scheme, the ONUs are divided into two groups, i.e., lightly loaded ONUs and heavily loaded ONUs, and the bandwidth savings from the lightly loaded ONUs are distributed among the heavily loaded ONUs. However, there is no suitable DBA algorithm for a hybrid network combining the FTTH access terminals and the WSN that can improve the fairness of bandwidth sharing between these two different service providers to reduce the end-to-end packet delay and improve the QoSs of a PON-based access network.

This section presents two variants of the proposed algorithm that improves the network performance and bandwidth sharing efficiency in the upstream channel of a hybrid PON that combines the FTTH access terminals and the WSN. The algorithm is called the adaptive limited DBA (ALDBA) algorithm. Unlike the existing algorithms, the ALDBA algorithm is not limited to controlling just the FTTH access networks, it also supports the WSNs. In the proposed algorithm, the difference in the lengths of generated data packets between the FTTH terminals and sensor nodes of the WSN has been investigated to effectively evaluate the end-to-end average packet delay, bandwidth utilization, jitter, upstream efficiency, and throughput. This thesis has investigated two variants of the proposed ALDBA algorithm called ALDBA1 and ALDBA2 schemes. In the ALDBA1 scheme, two different maximum transmission windows, $W_{WSN}^{\max}$ for the WSNs and $W_{FTTH}^{\max}$ for the FTTH access terminals, are considered and the available bandwidth saving is calculated from the difference of these two maximum transmission windows. Finally, the total available bandwidth saving is fairly distributed among all the ONUs of the network, regardless of the type of services. With the ALDBA2 scheme, the available bandwidth savings in the ALDBA1 scheme are used for the deferred data packets and this scheme is also incorporated into the EBR scheme of C. Assi et al. [29] without taking into consideration any intra ONU priority scheduling. This implies that all the data classes are transmitted on a FIFO basis.

4.1.1 Downstream and Upstream Frame Formats in a Single-OLT Hybrid PON

In the downstream direction of the proposed single-OLT hybrid PON, the OLT broadcasts the downstream data packets encapsulated with the Gate messages through a passive optical splitter. The destination ONUs selectively extract the broadcasted data packets from the OLT according to the destination addresses.

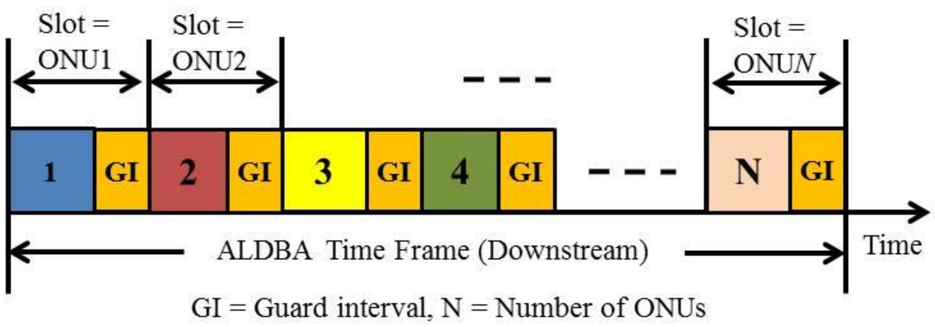


Fig. 4.1 Downstream frame format in a single-OLT hybrid PON.

Figure 4.1 shows the downstream data transmission in a single-OLT PON-based hybrid networks using the ALDBA schemes. In the downstream direction, the whole downstream transmission window is divided by the total number of ONUs *N*. These schemes consider the maximum downstream transmission windows for each ONU is same regardless of the service provider connected with the ONU. This downstream frame format is similar to that of the conventional PON.

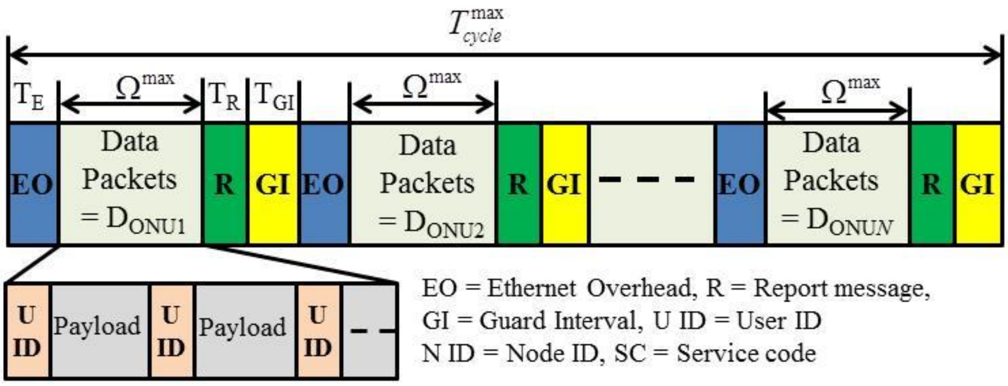


Fig. 4.2 Upstream frame format of a conventional PON with the LS scheme.

In every DBA algorithm, allocation of the upstream transmission window to an ONU depends on the requested window size Ω^R by that ONU and the maximum upstream window size Ω^{max} of the network. In the LS scheme, the maximum allocated window size Ω^{max} in the upstream direction depends on the maximum length of a time cycle, i.e., the maximum length of a polling cycle T_{cycle}^{max}, and the number of active ONUs N, as shown in the Fig. 4.2. Following equation is used to evaluate the maximum transmission window for an ONU in the upstream direction:

$$\Omega^{max} = \frac{T_{cycle}^{max} - N(T_E + T_R + T_{GI})}{N} \tag{4-1}$$

here, T_E is the length of the Ethernet overhead, T_R is the length of the Report message, and T_{GI} is the guard time.

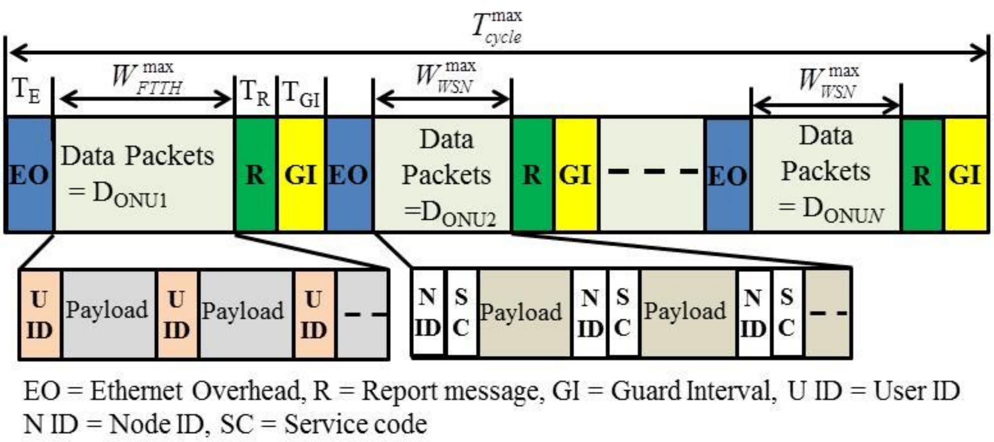


Fig. 4.3 Upstream frame format for the ALDBA schemes.

Fig. 4.3 shows the upstream frame format for the ALDBA schemes of the proposed single-OLT hybrid PON. Here, the ONU1 is an ONU connected to the FTTH terminal with the maximum window size, $W_{FTTH}^{\max}$ and the ONU2 is an ONU connected to the CH of a WSN with the maximum window size, $W_{WSN}^{\max}$. Every data packet of the ONU1 contains a user identification (ID) number and the payload of that user and may be multiplexed with different users if the ONU consists of multiple subscribers. In contrast, every data packet of the ONU2 contains a node ID number, a service code (SC), and the payload of the sensor node, which can be multiplexed with the payloads of different sensor nodes of different services. Here, the node ID is a unique number for each sensor node, and the SC indicates the type of service, i.e., gas, water, electricity, etc., and a code for a service provider (for discrimination if the same service is provided by different service providers) so that each sensor node can be uniquely recognized.

4.1.2 ALDBA 1 Scheme

In the ALDBA1 scheme, a hybrid PON-based access network with N ONUs from both the service providers is considered. The number of ONUs connected to the CHs of a WSN is N_{WSN} and the number of ONUs connected to the FTTH terminals is N_{FTTH}, i.e., $N = N_{WSN} + N_{FTTH}$. In every DBA scheme, the T_{cycle} is a variable parameter that varies from a minimum value to an upper bound, depending on the number of active ONUs and their traffic loads. Making the T_{cycle} too small will result in more bandwidth being wasted and not utilized by the Ethernet overheads (EOs), guard intervals (GIs), and Report messages, as shown in the Fig. 4.3. This is because even if an active ONU does not have any data, it still has to transmit a Report message that includes an EO and a GI. The maximum transmission window of an ONU always does not depend on the packet length but on the total stored data packets after the latest upstream transmission. However, typical transmission windows of the ONUs of WSN are less than that of the FTTH access network because of the lower data rate and smaller packet length of the WSN. That is why enclosing these two different operators' data in a single PON will make T_{cycle} smaller and the network will suffer from the bandwidth utilization problems. To overcome this problem and to improve the bandwidth sharing efficiency and QoSs of the proposed hybrid PON, two different $\Omega^{\max}$ are used, i.e., $W_{WSN}^{\max} < \Omega^{\max}$ for the WSN and $W_{FTTH}^{\max} = \Omega^{\max}$ for the FTTH access network, depending on the maximum length of generated packets by the ONUs of the FTTH access network and WSN. Since $W_{WSN}^{\max} < \Omega^{\max}$, the total available bandwidth savings W_{TS} are calculated using the equation below:

$$W_{TS} = N_{WSN}\left(\Omega^{\max} - W_{WSN}^{\max}\right) \tag{4.2}$$

Finally, the W_{TS} calculated in the Eq. 4.2 is divided by the total number of ONUs N to calculate the average available bandwidth savings for each ONU, i.e., $W^{avg}=W_{TS}/N$, and this average bandwidth savings is added to the maximum window $W_{FTTH}^{\max}$ or $W_{WSN}^{\max}$ if the requested window W^R is larger than the $W_{FTTH}^{\max}$ or $W_{WSN}^{\max}$.

The allocated transmission window for the ALDBA1 scheme is calculated using the following formula:

$$W_{i,j}^{ALDBA1} = \begin{cases} W_{i,j}^{R} & \text{if } W_{i,j}^{R} \le W_{i,j}^{\max} + W^{avg} \\ W_{i,j}^{\max} + W^{avg} & \text{if } W_{i,j}^{R} > W_{i,j}^{\max} + W^{avg} \end{cases} \tag{4.3}$$

where, $W_{i,j}^{ALDBA1}$ is the window size allocated to the ONU i at the time cycle j using the ALDBA1 scheme, and $W_{i,j}^{R}$ is the requested window size from the ONU i at the time cycle j, and $W_{i,j}^{\max}$ is the maximum window size for the ONUs connected to the FTTH terminals or the CHs of a WSN at the time cycle j.

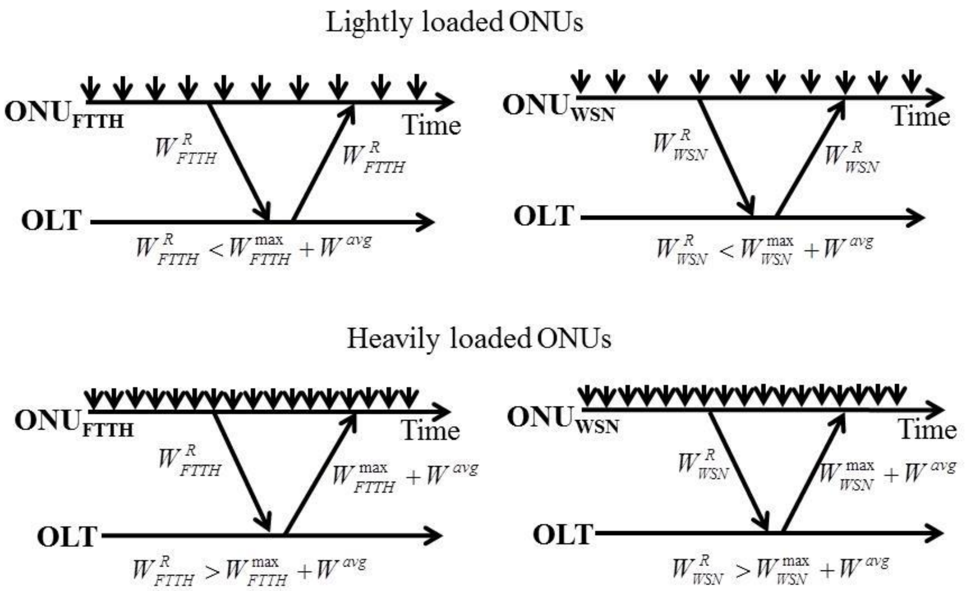


Fig. 4.4 Data acquisition in the ONUs and the ALDBA1 principles.

Figure 4.4 shows data acquisition in the ONUs connected to both the FTTH terminals and CHs of a WSN using the ALDBA1 principles for both the lightly loaded and heavily loaded ONUs. In this figure, the horizontal lines represent the time axes. In contrast, the vertical arrows represent the time instants for data arrival. The upper part of this figure shows data acquisition for the lightly loaded ONUs for both the ONUs connected to the FTTH terminal, in the left figure, and the CH of a WSN, in the right figure. In this case, the requested window sizes from both the ONUs are smaller than their corresponding maximum window sizes plus average bandwidth savings, i.e.,

$W_{FTTH/WSN}^{R} < W_{FTTH/WSN}^{\max} + W^{avg}$, thus the requested window sizes $W_{FTTH/WSN}^{R}$ are granted by the OLT. The lower part of this figure shows the data acquisition for the heavily loaded ONUs for both the ONUs connected to the FTTH terminal, in the left figure, and the CH of a WSN, in the right figure. In this case the requested window sizes from both the ONUs are higher than their corresponding maximum window sizes plus average bandwidth savings, i.e., $W_{FTTH/WSN}^{R} > W_{FTTH/WSN}^{\max} + W^{avg}$, thus the maximum window sizes plus average bandwidth savings $W_{FTTH/WSN}^{\max} + W^{avg}$ are granted by the OLT.

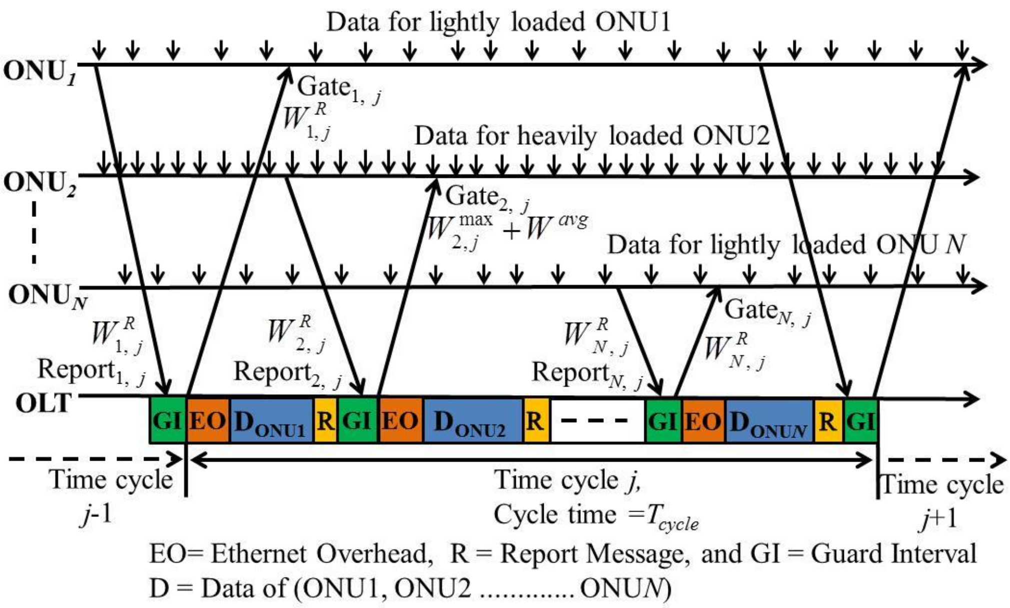


Fig. 4.5 Illustrated example of the ALDBA1 scheme.

Fig. 4.5 shows an illustrative example of the ALDBA1 scheme. If the ONU1 at the time cycle j is a lightly loaded ONU, i.e., $W_{1,j}^{R} < W_{1,j}^{\max} + W^{avg}$, then the granted window size is $W_{1,j}^{R}$. In contrast, if the ONU2 at the time cycle j is a heavily loaded, i.e., $W_{2,j}^{R} > W_{2,j}^{\max} + W^{avg}$, then the granted window size is $W_{2,j}^{\max} + W^{avg}$.

4.1.3 ALDBA 2 Scheme

In this scheme, excessive bandwidth from the lightly loaded ONUs, as explained in the EBR scheme by C. Assi et al. [29], is calculated without taking into consideration intra ONU priority scheduling. The ALDBA2 scheme is also incorporated with the average bandwidth savings in the ALDBA1 scheme to provide some transmission windows to the deferred data of an ONU during the waiting time between the transmission of the Gate and Report messages. To calculate the excessive bandwidth, the ONUs are divided into two groups: heavily loaded ONUs and lightly loaded ONUs. Equation 4.4 is used to calculate the total excessive bandwidth of the proposed hybrid PON.

$$W_{Total,j}^{excess} = \sum_{m=1}^{L_{FTTH}} \left(W_{FTTH,j}^{\max} - W_{m,j}^{R} \right) + \sum_{n=1}^{L_{WSN}} \left(W_{WSN,j}^{\max} - W_{n,j}^{R} \right) \tag{4.4}$$

where, $W_{Total,j}^{excess}$ is the total excessive bandwidth at the time cycle j, L_{FTTH} and L_{WSN} are the number of lightly loaded ONUs connected to the FTTH terminals and CHs of a WSN, respectively, and $W_{m/n,j}^{R}$ is the requested window size of the lightly loaded ONU *m/n* at the time cycle *j*.

The following equation is used to fairly distribute the total excessive bandwidth calculated in the Eq. 4.4 among the heavily loaded ONUs to solve the congestion problem in the hybrid PON:

$$W_{i,j}^{excess} = \frac{W_{Total,j}^{excess}}{\sum_{k=1}^{H} W_{k,j}^{R}} \times W_{i,j}^{R} \tag{4.5}$$

where, $W_{i,j}^{excess}$ is the excessive bandwidth for the ONU *i* at the time cycle *j* and *H* is the number of heavily loaded ONUs.

Usually, the waiting time in a PON is determined by the RTT and the delay time of Gate starting T_{GD} of each ONU. However, for simplicity, only the RTT delay is considered in the ALDBA2 scheme. The OLT predicts the amount of deferred data during the waiting time of each ONU and allocates the extra bandwidth up to the W^{avg} in addition to the requested window W^{R}. Prediction of the deferred data during the waiting time depends on the current queue occupancy and the RTT of each ONU, as shown in the equation below:

$$W_{i,j}^{pred} = \frac{RTT}{T_{i,j}^{acq}} \times W_{i,j}^{R} \tag{4.6}$$

where, $T_{i,j}^{acq}$ is the acquisition time of the present data in the queue of the ONU *i* at the time cycle *j*, $W_{i,j}^{pred}$ is the predicted window size for the ONU *i* at the time cycle *j*, and $W_{i,j}^{pred} \le W^{avg}$.

The main differences between the proposed ALDBA2 scheme and the existing EBR scheme in [29] are as follows:

1. Consideration of two different maximum transmission windows W^{max} for the two different services.
2. More priority is given to the heavily loaded ONUs by allocating the excessive bandwidth rather than the intra ONU priority scheduling among the different service classes.
3. Prediction of the waiting time traffic that is served by the average available bandwidth

savings W^{avg}.

The bandwidth allocation formula for the ALDBA2 scheme is as follows:

$$W_{i,j}^{ALDBA2} = \begin{cases} W_{i,j}^{R} + W_{i,j}^{pred} & \text{if } W_{i,j}^{R} \le W_{i,j}^{\max} + W_{i,j}^{excess} \\ W_{i,j}^{\max} + W_{i,j}^{excess} + W_{i,j}^{pred} & \text{if } W_{i,j}^{R} > W_{i,j}^{\max} + W_{i,j}^{excess} \end{cases} \quad (4.7)$$

where, $W_{i,j}^{ALDBA2}$ is the allocated bandwidth for the ONU *i* at the time cycle *j* using the ALDBA2 scheme.

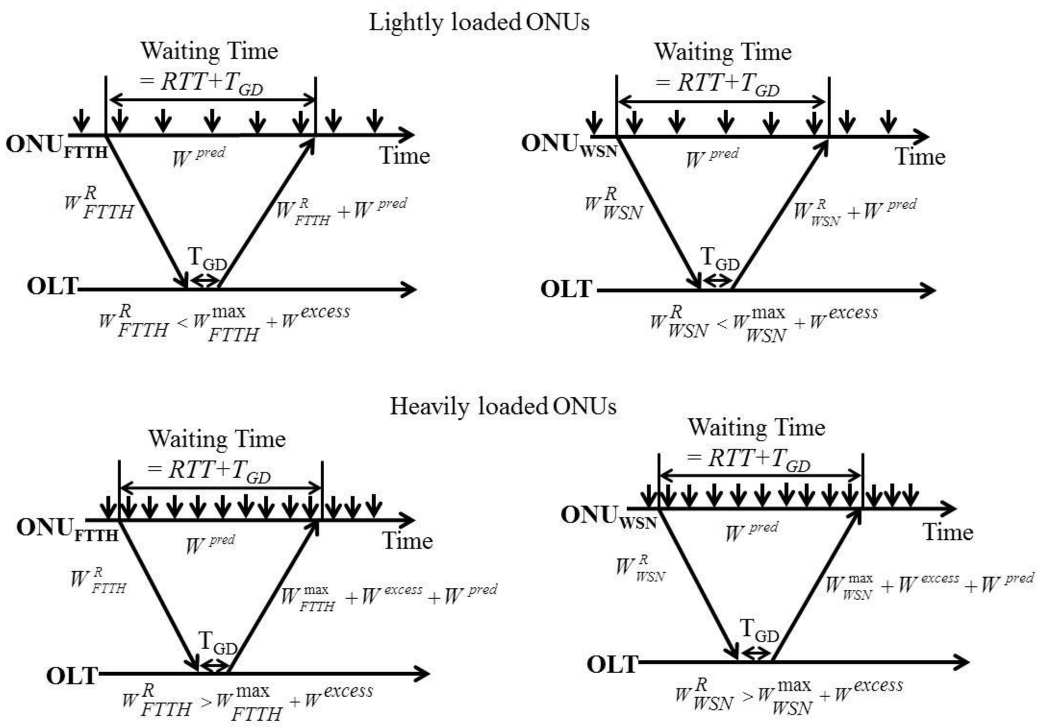


Fig. 4.6 Data acquisition in the ONUs and the ALDBA2 principles.

Figure 4.6 shows data acquisition in the ONUs connected to both the FTTH terminals and CHs of a WSN and calculation of the waiting time using the ALDBA2 principles. In this figure, the horizontal lines represent the time axes and the vertical arrows represent time instants for data arrival. In the case of the lightly loaded ONUs, shown in the upper part of the figure, left side for the FTTH terminals and right side for the CHs of a WSN, the requested window sizes from both the ONUs are smaller than their corresponding maximum window sizes plus the average excessive bandwidth from the lightly loaded ONUs, i.e., $W_{FTTH/WSN}^{R} < W_{FTTH/WSN}^{\max} + W^{excess}$, thus the requested windows with the predicted window $W_{FTTH/WSN}^{R} + W^{pred}$ are granted by the OLT. In contrast, the data acquisition for the heavily loaded ONUs are shown in the lower part of the figure for both the ONUs connected to the FTTH terminals, left side, and CH of WSN, right side. In this case, the requested window sizes from both the ONUs are higher than their corresponding maximum window sizes plus the average excessive bandwidth from the lightly loaded ONUs, i.e., $W_{FTTH/WSN}^{R} > W_{FTTH/WSN}^{\max} + W^{excess}$, thus the maximum windows with the ecessive and predicted windows $W_{FTTH/WSN}^{\max} + W^{excess} + W^{pred}$ are granted by the OLT.

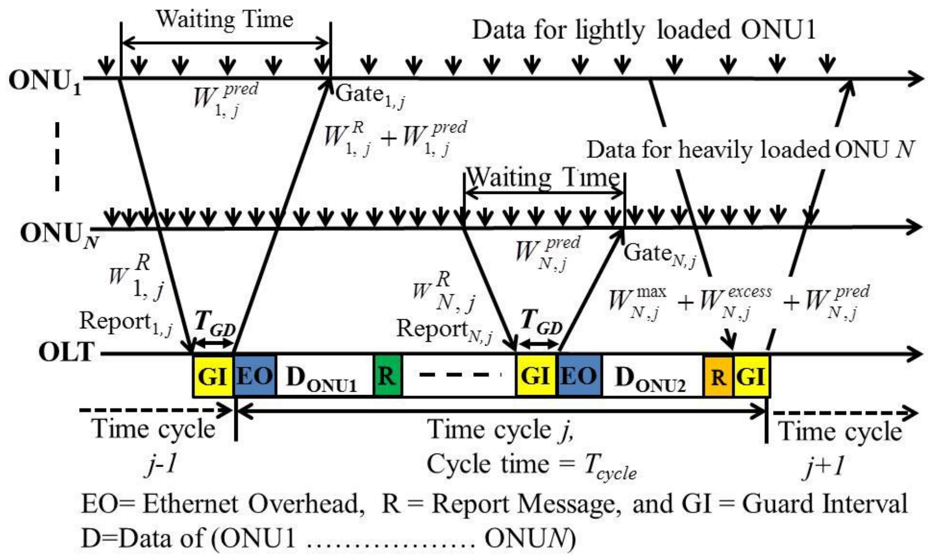


Fig. 4.7 Illustrative example of the ALDBA2 scheme.

The illustrative example of bandwidth allocation in the ALDBA2 scheme is shown in Fig. 4.7. Here, the requested window $W_{1,j}^{R}$ with the predicted window $W_{1,j}^{pred}$ is allocated to the lightly loaded ONU1 at the time cycle j. In contrast, the maximum transmission window $W_{N,j}^{\max}$ and the excessive bandwidth $W_{N,j}^{excess}$ with the predicted window $W_{N,j}^{pred}$ are allocated to the heavily loaded ONU N at the time cycle j.

4.2 Adaptive Limited DBA Algorithm for the Multi-OLT Hybrid PON (ALDBAM)

The proposed multi-OLT PON-based hybrid network, explained in the previous chapter, is an effective network structure for reducing the guard time between every two successive ONUs and the computational complexity for data packet processing. However, a new DBA scheme is also required for the multi-OLT hybrid PON for obtaining optimum services from the networks. In a TDM PON, the system performance depends on the sharing efficiency of the upstream channel. A DBA algorithm is very important for a TDM PON in improving the efficiency and bandwidth management in the upstream channel.

Intensive researches have been conducted on the DBA algorithms over the PON system. Among them, the proposed ALDBA algorithms, explained in the previous section of this thesis, are more prefered for the multi-OLT PON-based hybrid networks because these algorithms consider two different maximum transmission windows, $W_{FTTH}^{\max}$ for the ONUs connected the FTTH terminals and $W_{WSN}^{\max}$ for the ONUs connected to the CHs of a WSN, for two different service providers to improve the bandwidth sharing efficiency among them. However, there is a possibility of utilizing the guard time savings for the heavily loaded ONUs, which can improve the QoSs for a multi-OLT PON-based hybrid network. Moreover, all the existing DBA algorithms including the ALDBA algorithms have been proposed for a single-OLT PON, and without any modification, they are not suitable for the multi-OLT PON-based hybrid networks. One of the main reasons is that in a multi-OLT PON a single polling table will be shared by all the OLTs that requires modification in the MPCP [53] and control message scheduling algorithm.

This section explains a new DBA algorithm proposed for the multi-OLT PON called ALDBAM algorithm. The proposed scheme is a modified version of the ALDBA algorithms that explains in the previous section, where both the ALDBA1 and ALDBA2 schemes are combined with the proper guard time management and a modified MPCP.

4.2.1 Downstream and Upstream Frame Formats in a Multi-OLT Hybrid PON

For simplicity only two OLTs for two different service providers, i.e., FTTH and WSNs, are considered. In the downstream direction of the multi-OLT PON, each OLT alternately broadcasts data packets to the *N* ONUs of both service providers through a passive splitter. Where, *N*/2 ONUs are for the FTTH terminals and *N*/2 ONUs are for the WSN. The destination ONUs selectively extract the broadcasted data from the two OLTs. Here, OLT1 is considered as an OLT for the FTTH traffics and OLT2 is considered as an OLT for the WSN traffics. Hence, ONUs connected to the FTTH terminals accept the data packets from the OLT1 and ONUs connected the CHs of a WSN accept the data packets from the OLT2.

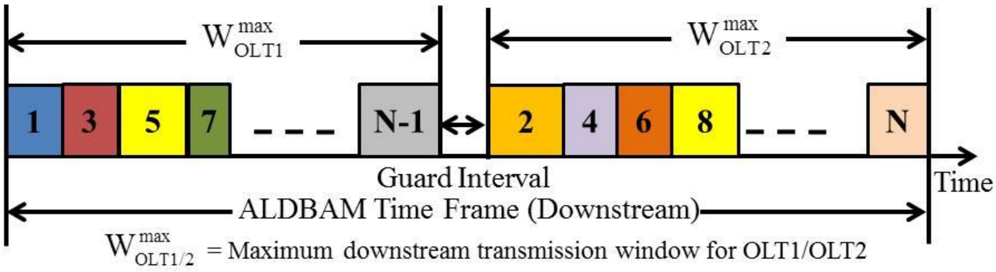


Fig. 4.8 ALDBAM downstream frame format in a multi-OLT hybrid PON.

Figure 4.8 shows the downstream frame format in a multi-OLT PON using the ALDBAM scheme. According to the principle of the ALDBAM scheme two different maximum downstream transmission windows for two different service providers, i. e., W^{max}_{OLT1} is the maximum transmission window from the OLT1 to the ONUs of the FTTH terminals, here, ONUs 1, 3, 5, … *N*-1, and W^{max}_{OLT2} is the maximum transmission window from the OLT2 to the ONUs of the WSN, here, ONUs 2, 4, 6, … *N*, are considered. Consequently, the OLT1 broadcasts the downstream data packets and the Gate messages to the ONUs 1, 3, 5, … *N*-1. In contrast, the OLT2 broadcasts the downstream data packets and the Gate messages to the ONUs 2, 4, 6, … *N*.

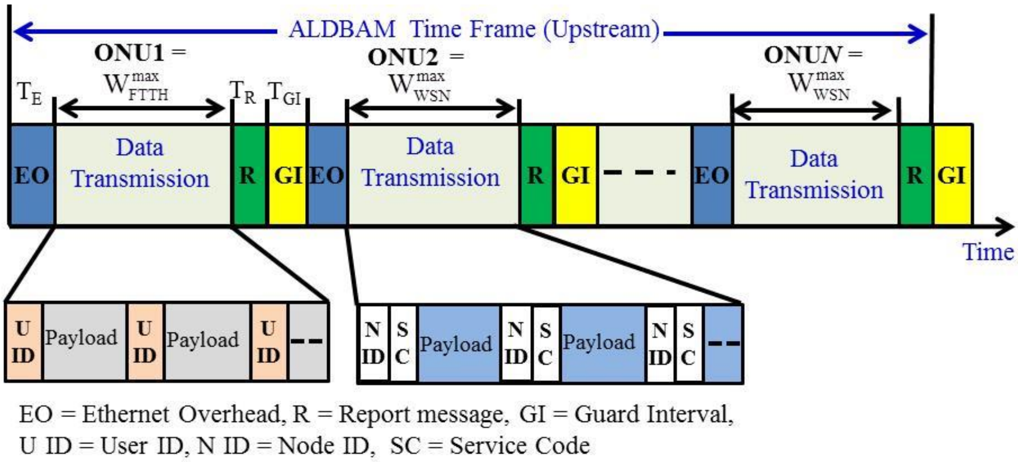


Fig. 4.9 ALDBAM upstream frame format in a multi-OLT hybrid PON.

In the upstream direction of the multi-OLT PON, data packets from any ONU will reach to both of the OLTs. However, data packets from an ONU will be accepted only by the designated OLT. Other OLTs will discard the data packets from that ONU and will wait for the data packets from the next ONU. Figure 4.9 shows the upstream frame format of the hybrid multi-OLT PON using the ALDBAM scheme. Here, the ONU1 is an ONU connected to the FTTH terminal communicating with the OLT1. In contrast, the ONU2 is an ONU connected to the CH of a WSN communicating with the OLT2. The upstream frame format of the ALDBAM scheme looks like the upstream frame format of the ALDBA schemes. However, the GI in the ALDBAM scheme is far smaller than the GI in the ALDBA schemes as explained in the subsections 3.1.3 and 3.2.3.

4.2.2 ALDBAM Scheme

In this scheme, a hybrid multi-OLT PON-based access network with two OLTs and N ONUs of two different service providers are considered. Here, N is divided into two groups and $N = N_{FTTH} + N_{WSN}$, where N_{FTTH} is the number of ONUs connected to the FTTH terminals and N_{WSN} is the number of ONUs connected to the CHs of a WSN. Usually, the packet size of the WSN is smaller, and the data rate is lower than those of the FTTH access network. This is why, the usual maximum transmission window of the WSN is smaller than the maximum transmission window of the FTTH terminals, i.e., $W_{WSN}^{\max} < W_{FTTH}^{\max}$. Owing to these packet length and data rate differences, the total available bandwidth savings in the proposed scheme, W_{TS}, is calculated by the Eq. 4.2 as in the ALDBA1 scheme explained in the previous section:

This W_{TS} is divided by N to calculate the average available bandwidth savings for each ONU, i.e., $W^{avg} = W_{TS}/N$, and this average bandwidth savings is used to provide some transmission windows to the deferred data during the waiting time between the transmission of the Gate and Report messages. Usually, the waiting time in a PON is equal to the RTT of each ONU and delay of the Gate starting time from the OLT. The OLTs predict the amount of deferred data during the waiting time for each ONU and allocate the additional bandwidth up to the W^{avg} in addition to the granted windows G_{OLT1} or G_{OLT2}. Prediction of the deferred data during the waiting time depends on the current queue occupancy, the RTT of each ONU, and the Gate starting delay from the OLTs:

$$W_{i,j}^{pred\_m} = \frac{RTT_i + T_{GD_i}}{T_{i,j}^{acq}} \times W_{i,j}^{R} \tag{4.8}$$

where, $W_{i,j}^{pred\_m}$ is the predicted window size for the ONU i of the multi-OLT PON at the time cycle j, $T_{i,j}^{acq}$ is the acquisition time of the present data in the queue of the ONU i at the time cycle j, $W_{i,j}^{R}$ is the requested window by the ONU i at the time cycle j, T_{GD_i} is the Gate starting delay for the ONU i, and the predicted window size is upper bounded by the average bandwidth savings, i.e., $W_{i,j}^{pred\_m} \le W^{avg}$.

Owing to the bursty nature of the network traffic [64], some ONUs might have traffic demand less than the $W_{FTTH}^{\max}$ or $W_{WSN}^{\max}$, called lightly loaded ONUs, while other ONUs might have traffic demand higher than the $W_{FTTH}^{\max}$ or $W_{WSN}^{\max}$, called heavily loaded ONUs. This results in some amount of excessive bandwidth from the lightly loaded ONUs. The total excessive bandwidth $W_{Total,j}^{excess}$ in the hybrid multi-OLT PON is also calculated as in the ALDBA2 scheme [21] explained in the previous section.

In the ALDBAM scheme, this total excess bandwidth from the lightly loaded ONUs is incorporated with the total guard time savings T_{GI_TS} in the Eq. 3.5. These two excess bandwidth savings from the Eqs. 3.5 and 4.4 can be fairly distributed to the heavily loaded ONUs, without changing the length of a time cycle T_{cycle}. The following equation is used to fairly distribute the total excessive bandwidth in the Eq. 4.4 and the total guard time savings in the Eq. 3.5 among the heavily loaded ONUs to solve the congestion problem in the hybrid multi-OLT PON:

$$W_{i,j}^{excess\_m} = \frac{W_{Total,j}^{excess} + T_{GI\_TS}}{\sum_{k=1}^{H} W_{k,j}^{R}} \times W_{i,j}^{R} \tag{4.9}$$

where, $W_{i,j}^{excess\_m}$ is the excessive bandwidth for the ONU *i* of the multi-OLT PON at the time cycle *j* and *H* is the number of heavily loaded ONUs in the network.

The bandwidth allocation formulas for the ALDBAM scheme in a multi-OLT PON are as follows:

$$G_{OLT1}^{i,j} = \begin{cases} W_{i,j}^{R} + W_{i,j}^{pred\_m} & \text{For lightly loaded ONUs} \\ W_{FTTH}^{\max} + W_{i,j}^{excess\_m} + W_{i,j}^{pred\_m} & \text{For heavily loaded ONUs} \end{cases} \tag{4.10}$$

$$G_{OLT2}^{i,j} = \begin{cases} W_{i,j}^{R} + W_{i,j}^{pred\_m} & \text{For lightly loaded ONUs} \\ W_{WSN}^{\max} + W_{i,j}^{excess\_m} + W_{i,j}^{pred\_m} & \text{For heavily loaded ONUs} \end{cases} \tag{4.11}$$

where, $G_{OLT1}^{i,j}$ is the granted window to the ONU *i* of the FTTH terminal by the OLT1 at the time cycle *j*, and $G_{OLT2}^{i,j}$ is the granted window for the ONU *i* of the WSN by the OLT2 at the time cycle *j*.

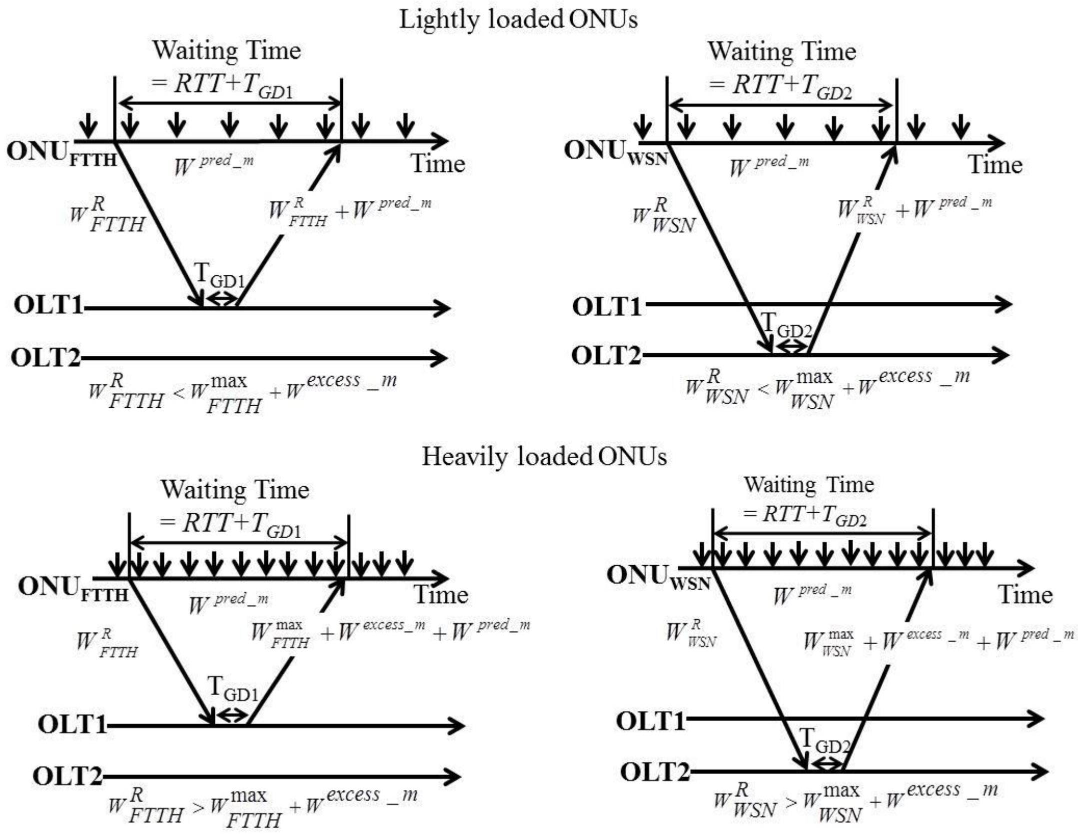
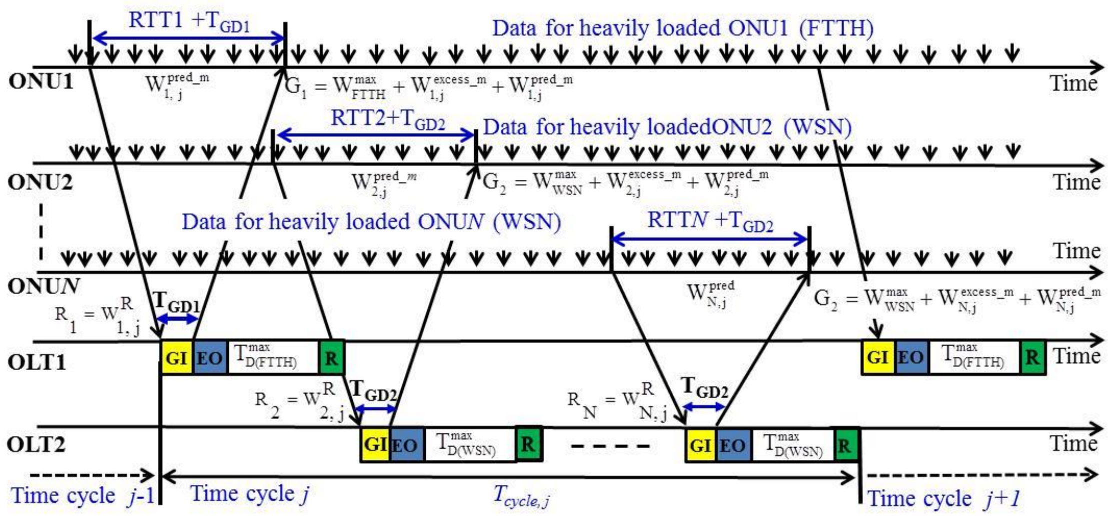


Fig. 4.10 Data acquisition in the ONUs and the ALDBAM principles.

Figure 4.10 shows data acquisition in the ONUs in a hybrid multi-OLT PON, and the ALDBAM principles. In this figure, the horizontal lines represent the time axes and the vertical arrows represent time instants for data arrival. Here, it is shown that the upstream data from the FTTH ONUs are transmitted to the OLT1. However, the FTTH data are also transmitted to the OLT2 as only passive splitter is used but the OLT2 does not accept the data from the ONUs connected to the FTTH terminals. In contrast, the OLT2 accepts data from the ONUs connected to the CHs of a WSN and the OLT1 discards the data from the ONUs connected to the CHs of a WSN. In the case of the lightly loaded ONUs, the requested window sizes from both the ONUs are smaller than their corresponding maximum window sizes plus average excessive bandwidth from the lightly loaded ONUs, i.e., $W_{FTTH/WSN}^{R} < W_{FTTH/WSN}^{\max} + W^{excess\_m}$. That is why, the granted window sizes are equal to the requested window sizes plus the predicted window size, $W_{FTTH/WSN}^{R} + W^{pred\_m}$. In contrast, for the heavily loaded ONUs the requested window sizes from both the service providers are higher than their corresponding maximum window sizes plus average excessive bandwidth from the lightly loaded ONUs, i.e., $W_{FTTH/WSN}^{R} > W_{FTTH/WSN}^{\max} + W^{excess\_m}$. Thus, the granted window sizes for the heavily loaded ONUs are equal to the corresponding maximum window sizes of both the service providers plus the average excessive bandwidth and the predicted window size, i.e., $W_{FTTH/WSN}^{\max} + W^{excess\_m} + W^{pred\_m}$.



$G_{1/2}$ = Gate message from OLT1/OLT2, $T_{GD1/2}$= Gate starting delay of OLT1/OLT2, RTT+T_{GD}= Waiting time, and R = Report message

Fig.4.11 Illustrative example of the ALDBAM scheme for the heavily loaded ONUs.

An illustrative example of the bandwidth allocation in the ALDBAM scheme for the heavily loaded ONUs is shown in Fig. 4.11. The bandwidth allocation conditions in the Fig. 4.11 follow the Eqs. 4.10 and 4.11 for the heavily loaded ONUs. Here, $T_{cycle,\,j}$ is the length of a polling cycle at the time cycle *j*. The maximum transmission window $W_{FTTH}^{\max}$ or $W_{WSN}^{\max}$ and the excessive bandwidths $W_{1,j}^{excess\_m}$, $W_{2,j}^{excess\_m}$, … $W_{i,j}^{excess\_m}$, … $W_{N,j}^{excess\_m}$ with the predicted windows $W_{1,j}^{pred\_m}$, $W_{2,j}^{pred\_m}$, … $W_{i,j}^{pred\_m}$, … $W_{N,j}^{pred\_m}$ are alternately allocated by the OLT1 or OLT2 to the heavily loaded ONUs 1, 2, … *i*, … *N* of both the service providers at the time cycle *j*. In contrast, the requested windows $W_{i,j}^{R}$ with $W_{i,j}^{pred\_m}$ are allocated by the OLT1 or OLT2 to the lightly loaded ONU *i* at the time cycle *j*, as shown in the Eqs. 4.10 and 4.11.

As network complexity increases with the history of internet development due to the inclusion of more diverse and new inconsistent functions [16], the ALDBAM scheme also requires more computational complexity than the LS scheme [17]. Because, the ALDBAM scheme needs to calculate the predicted traffic, excess bandwidth, and lightly loaded and heavily loaded ONUs that requires a larger number of summation and multiplication operations than the LS scheme. However, these complexities are not that much heavy to affect the online bandwidth allocation. Moreover, deployment of the multiple OLTs can share the overall complexities to reduce the computing time than the single-OLT PON.

The main differences between the proposed ALDBAM scheme and the ALDBA1 and ALDBA2 schemes explained in the previous sections are as follows:

1) Consideration of the multiple OLTs for the multiple service providers in a single PON.

2) Calculation of the total guard time savings by the proper guard time management in a multi-OLT PON and utilization of this guard time savings for the heavily loaded ONUs.

3) Appropriate modification of the MPCP for the multi-OLT hybrid PON.

4) Provision of detailed analysis of the upstream and downstream frame formats with the different maximum transmission windows for different OLTs and service providers.

5) Consideration of the Gate starting delay to calculate the predicted traffic in the waiting time.

6) Modification of the Gate message scheduling algorithm for a multi-OLT PON and the ALDBAM algorithm.

7) Sharing a single polling table by the two OLTs for upholding synchronization.

4.3 Conclusions

In this chapter, three new DBA algorithms have been proposed for the hybrid PON consisting of the FTTH and WSNs. The ALDBA1 and ALDBA2 schemes have been proposed for the single-OLT PON-based hybrid networks and the ALDBAM scheme has been proposed for the multi-OLT PON-based hybrid networks. All the proposed algorithms have investigated the differences in the packet lengths and data rates between the FTTH terminals and sensor nodes of a WSN. Since the packet lengths and data rates vary among the different service providers in a hybrid PON, the proposed hybrid PON has a poor bandwidth sharing efficiency when used with the existing DBAs.

In the ALDBA1 scheme, average bandwidth savings due to the smaller packet length in the WSN are utilized for the heavily loaded ONUs to provide better QoSs without increasing the length of a time cycle. In contrast, in the ALDBA2 scheme, total ONUs are divided into the heavily loaded and lightly loaded ONUs and the excess bandwidth from the lightly loaded ONUs are allocated for the heavily loaded ONUs to solve the congestion problem. In addition, the ALDBA2 scheme also uses the average bandwidth savings calculated in the ALDBA1 scheme for the deferred data during the waiting time between the Report and Gate messages.

The ALDBAM scheme enhances the performance of a multi-OLT PON by the reduction of data processing time, fair distribution of the excess bandwidth from the lightly loaded ONUs to the heavily loaded ONUs, proper guard time management, and the perfect scheduling algorithm of the Gate messages from the multiple OLTs.

5. Performance Analysis and Simulation Results of the Proposed DBA Schemes

In this chapter, the performances of the proposed single-OLT and multi-OLT hybrid PON-based FTTH and WSNs using the proposed ALDBA1, ALDBA2, and ALDBAM schemes are evaluated in terms of the average end-to-end packet delay, bandwidth utilization, jitter, upstream efficiency, and throughput. All these parameters are evaluated by simulation results. The evaluation was performed by laboratory made computer simulation programs. In all the proposed DBA algorithms, all the data packets were assumed to have the same priority, meaning the service policy was on a FIFO basis with an infinite buffer size for each ONU. A highly bursty self-similar network traffic model, as most network traffic can be characterized by the self-similarity and long range dependence (LRD) [64,65, 66], was used to generate the data packets for both the FTTH terminals and sensor nodes of the WSN. A self-similar object is an exact replica or approximately similar to a part of it, i.e., the whole has the same shape as one or more of the parts. Many objects in the real world, such as coastlines, are statistically self-similar: parts of them show the same statistical properties at many scales [67]. The self-similarity has important consequences for the design of network traffics or computer networks, as typical network traffic has the self-similar properties. For example, in the telecommunication engineering packet switched data traffic patterns seem to be statistically self-similar [68]. Hence, designing a network without taking into consideration of the self-similar traffics are not an expected way [69]. In the analysis, contour plots are used to represent the data for a wider range of offered loads and maximal cycle times. In all the contour plots, the horizontal axis represents the maximal cycle times in milli-second (ms) and the vertical axis represents the offered loads. Lighter colors signify better results for every analysis in every contour plot of this thesis. In comparing the results among the proposed and existing schemes a 2-ms cycle time is considered as a standard parameter where the horizontal axis represents a range of offered loads in every comparison.

5.1 Performance Analysis of the ALDBA1 Scheme

In this scheme, the architecture of a hybrid PON consisting of one OLT and 16 ONUs from both the FTTH access terminals and CHs of WSNs were considered. The transmission speed was considered as 1Gbps for both the upstream and downstream channels. The distances from the OLT to the ONUs were assumed to be random and in the range 10-20 km. The burst traffics from 0 to multiple packets were generated, where the length of each packet was not larger than the maximum packet length B_{max}. The maximum packet lengths for the FTTH terminals and WSNs were 1500 bytes

[70] and 1024 bytes [71], respectively. The ratio of the two maximum transmission windows, $W_{FTTH}^{\max}$ and $W_{WSN}^{\max}$, reflected the ratio of these two maximum packet lengths. The computation time was assumed to be 10 μs for the proposed DBA algorithms, as used by I. Hwang et al [52]. All the analyses were done for the non-uniform offered loads in the range 0-1.4 with the variable maximal cycle times in the range 0.5-3 ms. The simulations took into consideration the queuing delay, transmission delay, congestion delay, and processing delay without taking into consideration any priority scheduling. The simulation parameters are summarized in Table 5.1.

Table 5.1 Simulation parameters used in the single-OLT PON-based FTTH and WSN

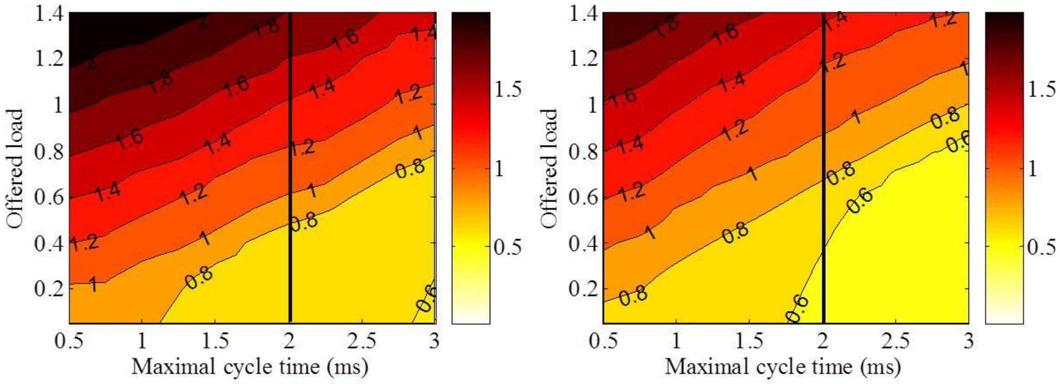
Symbol	Quantity	Value
N	Number of ONUs	16
m	Number of service providers	2
D	Distance between OLT and ONUs	10 to 20 km
B_{max}	Maximum packet lengths	1500 bytes (FTTH) 1024 bytes (WSN)
B_R	Length of Report message	576 bits
B_E	Length of Ethernet overhead	304 bits
T_{GI}	Guard time	5 μs
R_U	Transmission speed	1 Gbps
T_{proc}	Processing time	10 μs
P	Number of generated packets	0 to 20

5.1.1 Delay

The end-to-end packet delay is one of the most important parameters for every network. In a network, the end-to-end packet delay comprises of protocol delay, propagation delay, congestion delay, and processing delay. The proposed single-OLT hybrid PON consists of sensor networks and the data of some sensor nodes, e.g., hospital and fire alarm sensor systems, are delay sensitive. One of the main objectives of the proposed ALDBA1 algorithm is the reduction of the end-to-end packet delay by allocating larger transmission windows to the heavily loaded ONUs. The following equation is used to calculate the end-to-end packet delay D_{A1}, of the ALDBA1 scheme:

$$D_{A1} = \begin{cases} \dfrac{\sum_{i=1}^{N}(W_i^R + B_C)}{R_U} & \text{if } W_i^R < W_i^{\max} + W^{avg} \\ \dfrac{\sum_{i=1}^{N}(W_i^{\max} + W^{avg} + B_C)}{R_U} + T_{cng} & \text{if } W_i^R \geq W_i^{\max} + W^{avg} \end{cases} \tag{5.1}$$

here, W_i^R is the requested window size by the ONU i, $W_i^{\max}$ is the maximum window size of the ONU i, W^{avg} is the average bandwidth savings, B_C is the summation of the B_R, B_E, and GI , and T_{cng} is the congestion delay.



(a) LS Scheme (b) ALDBA1 Scheme

Fig. 5.1 Average packet delay in a single-OLT PON-based hybrid networks for the LS and ALDBA1 schemes and N_{FTTH}:N_{WSN} = 8:8.

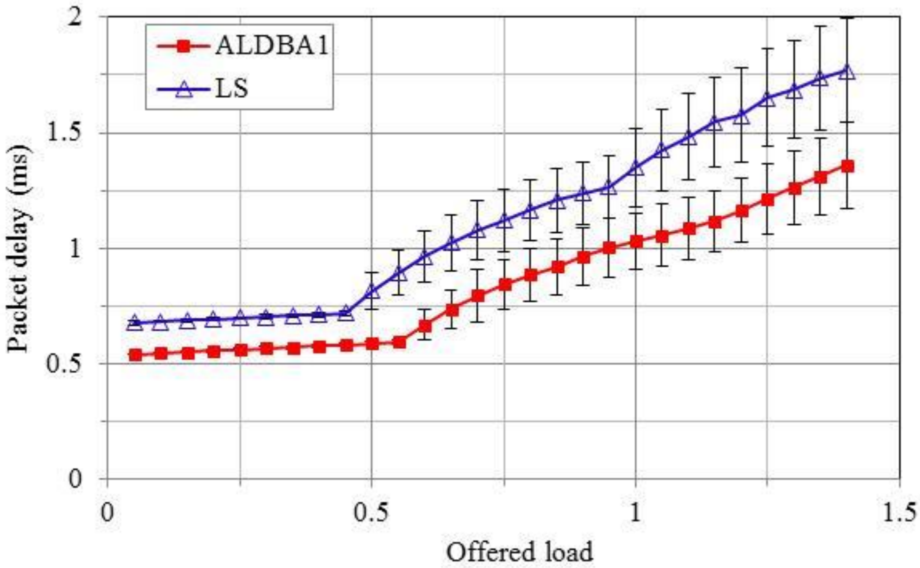
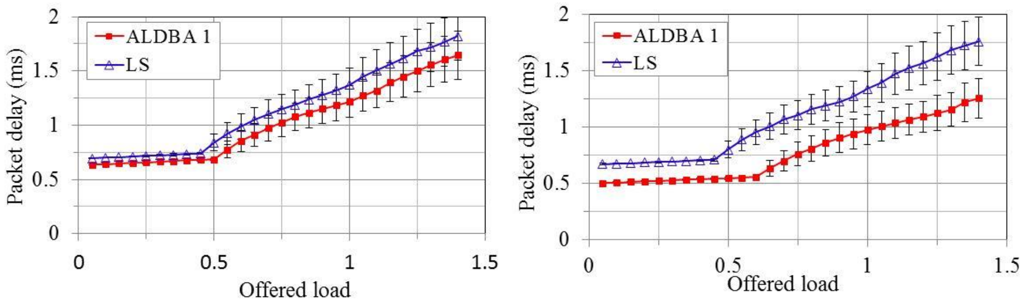


Fig. 5.2 Comparison of average packet delay between the LS and ALDBA1 schemes for a 2-ms cycle time and N_{FTTH}: N_{WSN} = 8:8.

Figures 5.1(a), and 5.1(b) show contour plots of the average end-to-end packet delay for different offered loads and cycle times of the existing LS and the proposed ALDBA1 schemes for N_{FTTH}:N_{WSN} = 8:8. From the analysis and comparison of these two contour plots, it is clear that the ALDBA1 scheme provides less delay than the LS scheme for any value of the cycle time and offered load. Comparison of the average packet delay among the two schemes is shown in Fig. 5.2 for a 2-ms cycle time and N_{FTTH}: N_{WSN} = 8:8. From this result, it is found that the ALDBA1 scheme provides about 25% less delay than the LS scheme at an offered load of 1.4.



(a) N_{FTTH}: N_{WSN} = 12:4 (b) N_{FTTH}: N_{WSN} = 4:12

Fig. 5.3 Comparison of average packet delay between the LS and ALDBA1 schemes for a 2-ms cycle time.

Figures 5.3 (a) and 5.3 (b) compare the average packet delay for the offered loads between the LS, and ALDBA1 schemes for a 2-ms cycle time by changing the number of ONUs connected to the FTTH terminals and CHs of WSN. From the comparison of the both cases, it is clear that the ALDBA1 scheme outperforms the LS scheme from a very lower offered load to higher offered load. The end-to-end packet delays for the proposed ALDBA1 scheme is far smaller than that for the LS scheme when the number of ONUs connected to the CHs of WSN is larger than those connected to the FTTH terminals, as shown in the Fig. 5.3 (b), where N_{FTTH} :N_{WSN} = 4:12. The main reason of this lower delay in the Fig. 5.3 (b) is due to the higher bandwidth savings from the larger number of ONUs connected to the CHs of WSNs.

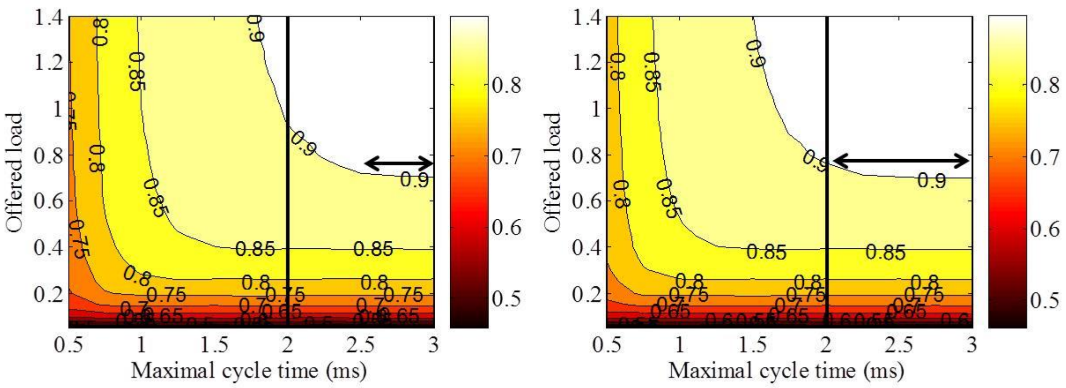
5.1.2 Bandwidth Utilization

The bandwidth utilization *BWU* of a PON system can be defined by the following formula:

$$BWU = \frac{W_{grant}^{total}}{W_{grant}^{total} + NB_C} \tag{5.2}$$

where, W_{grant}^{total} is the total granted window for all the active ONUs. Since the term NB_C in the denominator is a constant in every time cycle, the bandwidth utilization can be improved if a longer total granted window W_{grant}^{total} can be provided by taking into consideration the ONU's traffic. Note that the proposed scheme can achieve the better bandwidth sharing efficiency and can reduce unused bandwidth by using two different maximum transmission windows for both the types of ONUs connected to the FTTH and WSNs. Granting of this more transmission windows to the heavily loaded ONUs is the main reason why the proposed ALDBA1 scheme can improve the bandwidth utilization in a hybrid PON. The following equation is used to calculate the bandwidth utilization BWU_{A1} of the ALDBA1 scheme:

$$BWU_{A1} = \begin{cases} \dfrac{\sum_{i=1}^{N} W_i^R}{\sum_{i=1}^{N}\left(W_i^R + B_C\right)} & \text{if } W_i^R < W_i^{\max} + W^{avg} \\ \dfrac{\sum_{i=1}^{N}\left(W_i^{\max} + W^{avg}\right)}{\sum_{i=1}^{N}\left(W_i^{\max} + W^{avg} + B_C\right)} & \text{if } W_i^R \geq W_i^{\max} + W^{avg} \end{cases} \tag{5.3}$$



(a) LS scheme (b) ALDBA1 scheme

Fig. 5.4 Bandwidth utilization in a single-OLT PON-based hybrid networks for the LS and ALDBA1 schemes and N_{FTTH}:N_{WSN} = 8:8.

The contour plots of Fig. 5.4 show the bandwidth utilization of the existing LS and the proposed ALDBA1 schemes. From the analysis, it is found that the ALDBA1 scheme provides a wider area of the maximum bandwidth utilization than the LS scheme. Even though the Fig. 5.5 shows that both the ALDBA1 and LS schemes provide very close bandwidth utilization for a 2-ms cycle time, the ALDBA1 scheme could achieve the highest bandwidth utilization of 0.9 from 2 to 3-ms maximal cycle times with an offered load of 0.8 while the LS scheme could achieve the same result from 2.5 to 3-ms maximal cycle time with an offered load of 0.8, as shown using the black arrows in the contour plots of the Figs. 5.4; therefore, the ALDBA1 scheme is more suitable in term of bandwidth utilization even for the lower cycle time than that of the LS scheme.

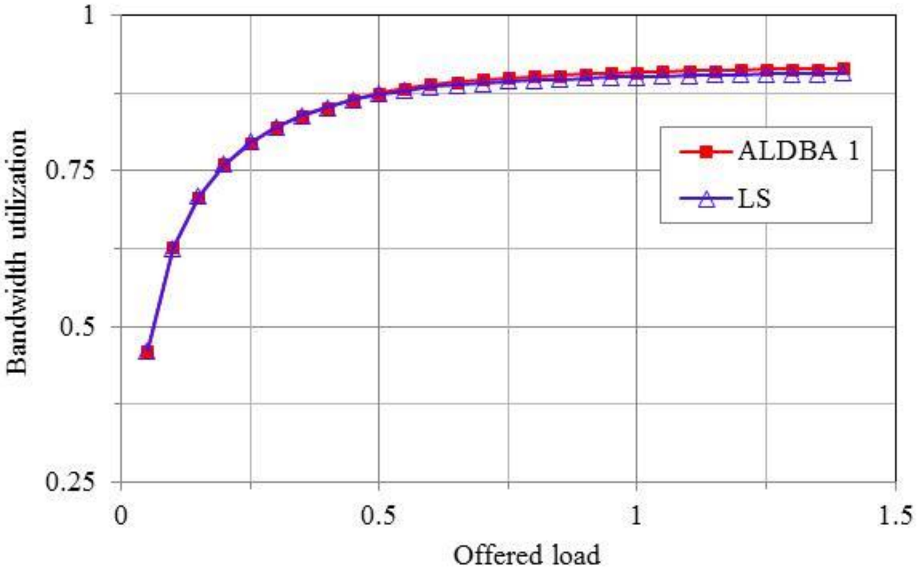


Fig. 5.5 Comparison of bandwidth utilization between the LS and ALDBA1 schemes for a 2-ms cycle time and N_{FTTH}: N_{WSN} = 8:8.

5.1.3 Upstream Efficiency

The upstream efficiency of a PON system is defined by the Eq. 5.4:

$$UE = \frac{W_{grant}^{total}}{W_{gen}^{total} + NB_C} \tag{5.4}$$

here, UE is the upstream efficiency in a PON, W_{gen}^{total} is the total generated window of all the active ONUs. The calculation of the W_{grant}^{total} in the Eq. 5.4 is similar to that of the BWU in the Eq. 5.2. However, the W_{gen}^{total} in the denominator of the upstream efficiency consists of a summation of the total generated windows of all the ONUs in a time cycle even when the generated window is greater than the W^{max}. Because of that the upstream efficiency can be lower than the bandwidth utilization. Equation 5.5 is used to calculate the upstream efficiency UE_{A1} for the ALDBA1 scheme:

$$UE_{A1} = \begin{cases} \dfrac{\sum_{i=1}^{N} W_i^R}{\sum_{i=1}^{N} \left(W_i^R + B_C\right)} & \text{if } W_i^R < W_i^{\max} + W^{avg} \\ \dfrac{\sum_{i=1}^{N} \left(W_i^{\max} + W^{avg}\right)}{\sum_{i=1}^{N} \left(W_i^R + B_C\right)} & \text{if } W_i^R \geq W_i^{\max} + W^{avg} \end{cases} \tag{5.5}$$

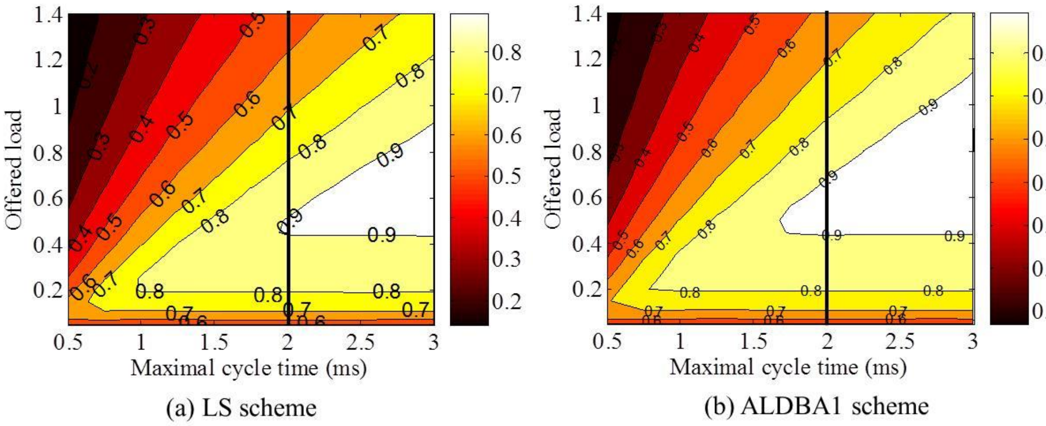


Fig. 5.6 Upstream efficiency in a single-OLT PON-based hybrid networks for the LS and ALDBA1 schemes and $N_{FTTH}:N_{WSN}$ = 8:8.

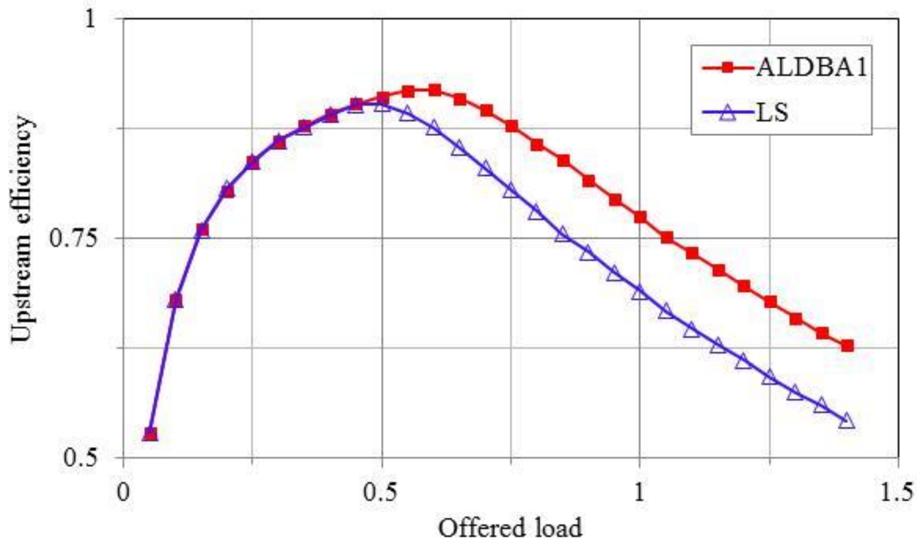


Fig. 5.7 Comparison of upstream efficiency between the LS and ALDBA1 schemes for a 2-ms cycle time and N_{FTTH}: N_{WSN} = 8:8.

Comparison of the upstream efficiencies for the same ranges of cycle time and offered load is shown by the contour plots in Figs. 5.6(a), and 5.6(b). In this case, the proposed ALDBA1 scheme is also better than the existing LS scheme; this result is consistent with all the above results. From the figures it is clear that the lowest upstream efficiency in the ALDBA1 scheme is 0.3 while the lowest upstream efficiency in the LS scheme is 0.2. Moreover, the ALDBA1 scheme provides a wider area of the highest upstream efficiency of 0.9 in both the directions of offered loads and maximal cycle times. The comparison of the upstream efficiency for a 2-ms cycle time in Fig. 5.7 shows that the upstream efficiency drops gradually for an offered load larger than 0.5 for the LS scheme and 0.6 for the ALDBA1 scheme. However, the lowest upstream efficiency in the ALDBA1 scheme at the highest offered load of 1.4 is higher than that of the LS scheme.

5.1.4 Jitter

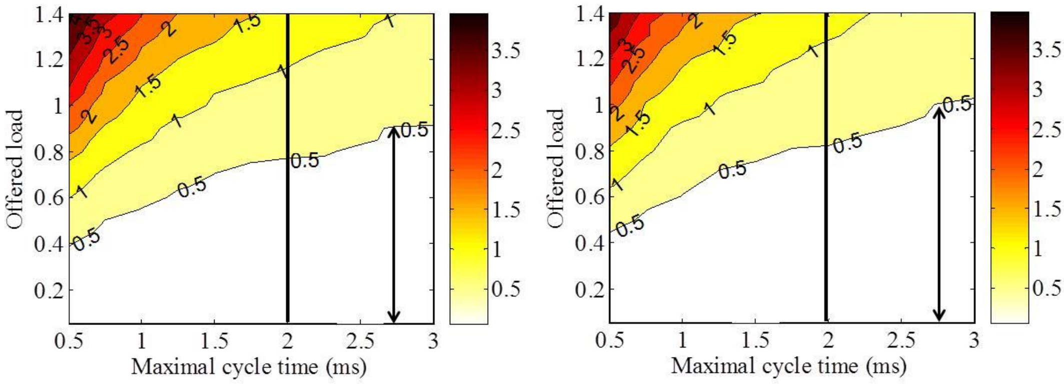
The nature of the usual network traffic models is highly bursty. Due to this bursty network traffic, the data packets of an ONU suffer from variations in arrival times in different time cycles. In any DBA scheme, the jitter cannot be avoided because the length of a cycle time is changed with the aggregated data packets of all the ONUs in every time cycle. To measure the variation of the data arrival times in every time cycle, jitter performance of the proposed ALDBA1 scheme is analyzed. The following equation is used to calculate the jitter J_{A1} in the ALDBA1 scheme:

$$J_{A1} = \sqrt{\frac{1}{q}\sum_{j=1}^{q}\left(T_{avl,j}^{A1} - T_{avl,j-1}^{A1}\right)^2} \tag{5.6}$$

here, q is the number of iterations, and $T_{avl,j}^{A1}$ is the arrival time of data packets at the time cycle j of the ALDBA1 scheme.

The data packet arrival time $T_{avl,j}^{A1}$ at the time cycle j in the ALDBA1 scheme can be calculated by using the Eq. 5.7:

$$T_{avl,j}^{A1} = \begin{cases} \dfrac{\sum_{i=1}^{N}\left(W_i^R + B_C\right)}{R_U} & \text{if } W_i^R < W_i^{\max} + W^{avg} \\ \dfrac{\sum_{i=1}^{N}\left(W_i^{\max} + W^{avg} + B_C\right)}{R_U} + T_{cng} & \text{if } W_i^R \geq W_i^{\max} + W^{avg} \end{cases} \tag{5.7}$$



(a) LS Scheme (b) ALDBA1 Scheme

Fig. 5.8 Jitter in a single-OLT PON-based hybrid networks for the LS and ALDBA1 schemes and $N_{FTTH}:N_{WSN} = 8:8$.

Jitter performances of the existing LS and the proposed ALDBA1 schemes are shown in Figs.

5.8(a), and 5.8(b). As shown using the black arrows in the contour plots, the ALDBA1 scheme provides the lowest jitter until the offered load of 1.0 at the 3-ms cycle time while the LS scheme provides the lowest jitter until the offered load of 0.85. In addition, the highest jitter in the ALDBA1 scheme is 3 ms while the highest jitter in the LS scheme is 3.5 ms.

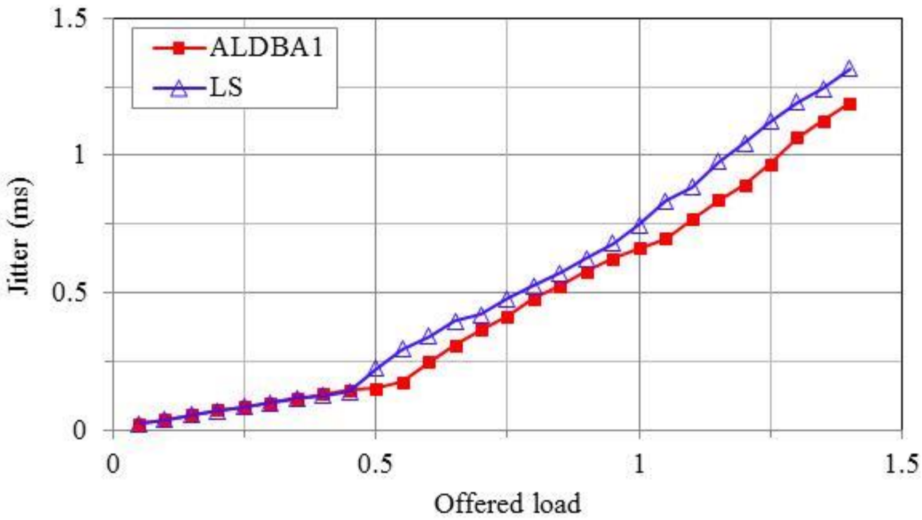
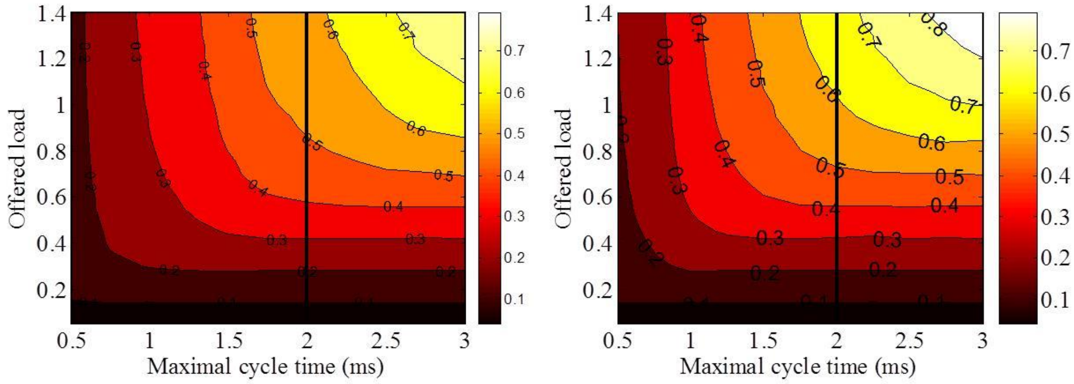


Fig. 5.9 Comparison of jitter between the LS and ALDBA1 schemes for a 2-ms cycle time and N_{FTTH}: N_{WSN} = 8:8.

From the comparison of the jitter for a 2-ms cycle time in Fig. 5.9, it is found that the ALDBA1 scheme performs slightly better than the LS scheme at offered loads larger than 0.5. However, the jitter is similar in both the schemes at offered loads lower than 0.5.

5.1.5 Throughput

In a communication network, throughput, the average rate of successful message delivery over a communication channel, is a very important parameter to define the network performance. Users of the telecommunication devices, systems designers, and the researchers in the communication theory are often interested in throughput for knowing the expected performance of a system. Figures 5.10(a) and 5.10(b) show the contour plots of the throughput for different offered loads and cycle times for the LS and ALDBA1 schemes, respectively. As expected, the proposed ALDBA1 scheme provides a higher throughput than the LS scheme in both the directions of offered loads and time cycles. This improvement of the throughput in the ALDBA1 scheme is achieved due to the utilization of the average bandwidth savings from the ONUs connected to the CHs of WSN for the heavily loaded ONUs.



(a) LS scheme (b) ALDBA1 scheme

Fig. 5.10 Throughput in a single-OLT PON-based hybrid networks for the LS and ALDBA1 schemes and $N_{FTTH}:N_{WSN}$ = 8:8.

g

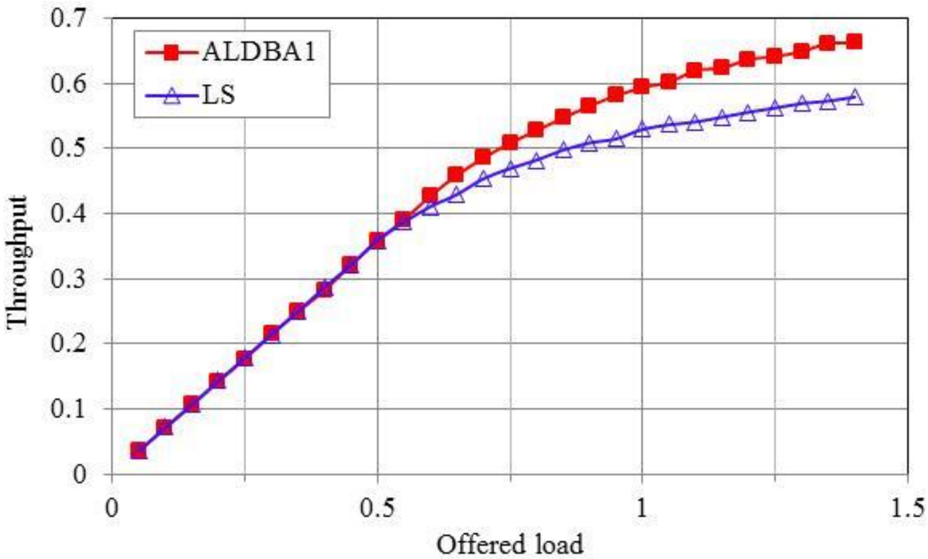


Fig. 5.11 Comparison of throughput between the LS and ALDBA1 schemes for a 2-ms cycle time and N_{FTTH}: N_{WSN} = 8:8.

Figure 5.11 compares the throughput between the LS and ALDBA1 schemes for a 2-ms cycle time. From this figure it is clear that both the LS and ALDBA1 schemes achieve same throughput up to the offered load of 0.55. However, the ALDBA1 scheme achieves a throughput of more than 65% at an offered load of 1.4 compared with the existing LS scheme achieving that of more than 55%.

5.2 Performance Analysis of the ALDBA2 Scheme

In this section, the performances of the proposed ALDBA2 scheme for the hybrid PON are evaluated in terms of the average end-to-end packet delay, bandwidth utilization, jitter, upstream efficiency, and throughput. All these performances are also compared to those of the ALDBA1 scheme explained in the previous section. The main differences of the ALDBA2 scheme than the ALDBA1 scheme are; (1) calculation of excess bandwidth savings from the lightly loaded ONUs and fair allocation of this excess bandwidth for the heavily loaded ONUs to reduce the data congestion, and (2) allocation of the average bandwidth savings from the ONUs connected to the CHs of WSN for the deferred data to reduce the waiting time in the queue. The evaluation was also performed by laboratory made computer simulation programs. All the evaluation parameters were similar to that of the ALDBA1 scheme and the parameters shown in the Table 5.1.

5.2.1 Delay

Two of the major causes those influences to increase the end-to-end packet delays in the PON systems are due to congestions and deferred data. The main objectives of the ALDBA2 scheme are: (1) to provide larger transmission windows for the congested ONUs from the lightly loaded ONUs, and (2) to provide some transmission windows for the deferred data by predicting the data traffics during the waiting time from the average bandwidth saving of the ONUs connected to the CHs of WSN. The following equation is used for the ALDBA2 scheme to calculate the end-to-end packet delay:

$$D_{A2} = \begin{cases} \dfrac{\sum_{i=1}^{N}(W_i^R + W_i^{pred} + B_C)}{R_U} & \text{if } W_i^R < W_i^{\max} + W_i^{excess} \\ \dfrac{\sum_{i=1}^{N}(W_i^{\max} + W_i^{excess} + W_i^{pred} + B_C)}{R_U} + T_{cng} & \text{if } W_i^R \geq W_i^{\max} + W_i^{excess} \end{cases} \tag{5.8}$$

here, D_{A2} is the end-to-end packet delay in the ALDBA2 scheme, W_i^{pred} is the predicted bandwidth for the ONU *i*, and W_i^{excess} is the excess bandwidth from the lightly loaded ONUs for the ONU *i*.

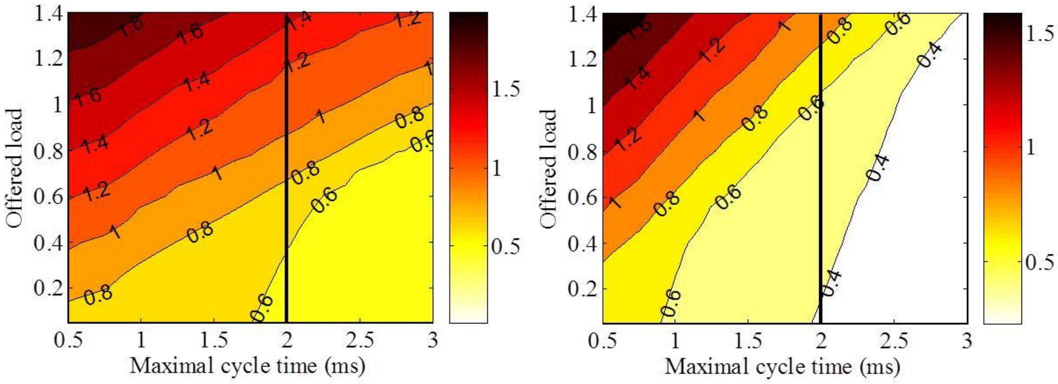


Fig. 5.12 Average packet delay in a single-OLT PON-based hybrid networks for the ALDBA1 and ALDBA2 schemes and $N_{FTTH}:N_{WSN}$ = 8:8.

Figures 5.12(a) and 5.12(b) show contour plots of the average end-to-end packet delay for different offered loads and cycle times of the ALDBA1 and ALDBA2 schemes for $N_{FTTH}:N_{WSN}$ = 8:8. From the analysis and comparison of these two contour plots, it is clear that the ALDBA2 scheme provides less delay than the ALDBA1 scheme for any value of a cycle time and offered load. The lowest delay in the ALDBA2 scheme is 0.4 ms while the lowest delay in the ALDBA1 scheme is 0.6 ms. These results signify that the consideration of the excess bandwidth savings from the lightly loaded ONUs for the heavily loaded ONUs and average bandwidth savings for the deferred data are very effective to reduce the end-to-end packet delay in the proposed hybrid PON-based FTTH and WSNs.

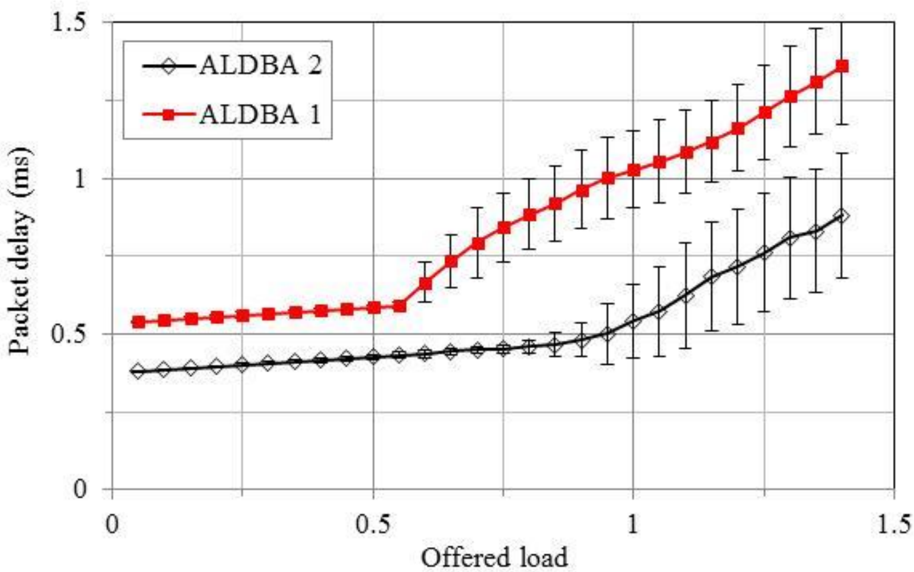
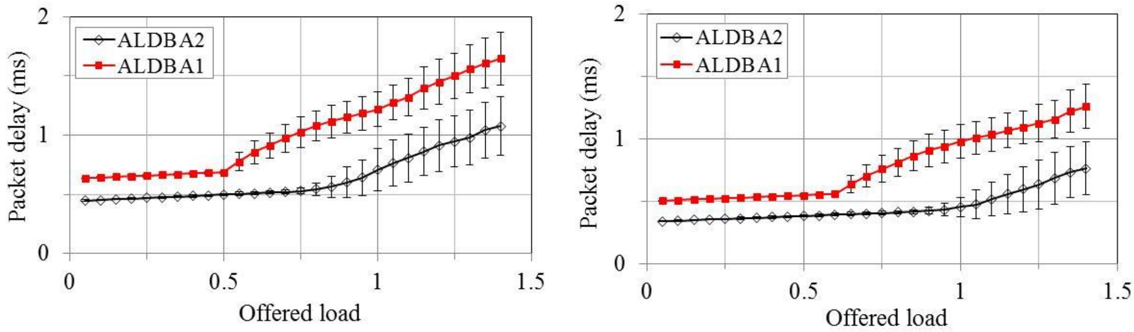


Fig. 5.13 Comparison of average packet delay between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time and N_{FTTH}: N_{WSN} = 8:8.

Figure 5.13 compares the average packet delay between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time. From this result, it is found that the ALDBA2 scheme provides about 25% less delay than the ALDBA1 scheme at an offered load of 1.4. Therefore, the ALDBA2 scheme provides the best delay performance in the proposed single-OLT hybrid PON. The proposed ALDBA2 scheme is also more suitable for the delay sensitive services, e.g., VoIP service. Since the VoIP uses real-time transport protocol, it requires a lower packet delay.



(a) N_{FTTH}: N_{WSN} = 12:4 (b) N_{FTTH}: N_{WSN} = 4:12

Fig. 5.14 Comparison of average packet delay between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time.

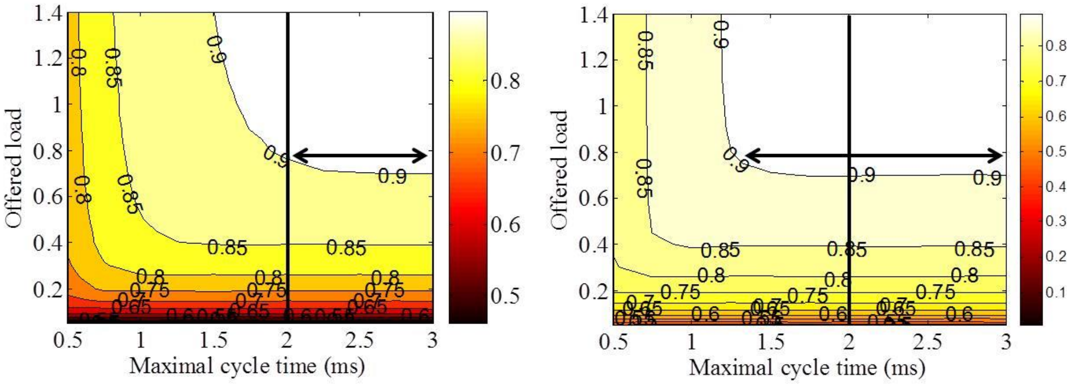
Figures 5.14(a) and 5.14(b) compare the average packet delay with the offered load between the ALDBA1, and ALDBA2 schemes for a 2-ms cycle time by changing the ratios of the number of ONUs connected to the FTTH terminals and CHs of WSN where the total number of ONUs remains constant. From the comparison of the both cases, i.e., N_{FTTH} :N_{WSN} = 12:4, and N_{FTTH} :N_{WSN} = 4:12 , it is clear that the ALDBA2 scheme outperforms the ALDBA1 scheme as shown in the Fig. 5.13. So the ALDBA2 scheme is being the best in all the cases of ONUs ratios. It can be concluded that the end-to-end packet delays for the ALDBA2 scheme is always far smaller than that of the ALDBA1 scheme in all the cases of the ONUs ratios as shown in the Figs. 5.13, 5.14(a) and 5.14(b). However, the average packet delays are far less in both the ALDBA1 and ALDBA2 schemes when the number of ONUs connected to the CHs of WSN is larger than those connected to the FTTH terminals, as shown in the Fig. 5.14(b), where N_{FTTH} :N_{WSN} = 4:12. The main reason is the higher bandwidth savings from the larger number of ONUs connected to the CHs of WSNs.

5.2.2 Bandwidth Utilization

As explained in the Eq. 5.2, the larger total granted window W_{grant}^{total} provides higher bandwidth utilization in a PON system. The ALDBA2 scheme provides larger transmission windows for the heavily loaded ONUs from the lightly loaded ONUs that means the effective granted window will be larger than the ALDBA1 and LS schemes. As a result the ALDBA2 scheme providers higher bandwidth utilization than both the ALDBA1 and LS schemes. The Eq. 5.9 is used to calculate the bandwidth utilization in the ALDBA2 scheme for a PON-based hybrid networks comprising the FTTH and WSNs:

$$BWU_{A2} = \begin{cases} \dfrac{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred}\right)}{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred} + B_C\right)} & \text{if } W_i^R < W_i^{\max} + W_i^{excess} \\ \dfrac{\sum_{i=1}^{N}\left(W_i^{\max} + W_i^{excess} + W_i^{pred}\right)}{\sum_{i=1}^{N}\left(W_i^{\max} + W_i^{excess} + W_i^{pred} + B_C\right)} & \text{if } W_i^R \geq W_i^{\max} + W_i^{excess} \end{cases} \quad (5.9)$$

here, BWU_{A2} is the bandwidth utilization in the ALDBA2 scheme.



(a) ALDBA1 scheme (b) ALDBA2 scheme

Fig. 5.15 Bandwidth utilization in a single-OLT PON-based hybrid networks for the ALDBA1 and ALDBA2 schemes and $N_{FTTH}:N_{WSN}$ = 8:8.

The contour plots of Figs. 5.15 show the bandwidth utilization of the ALDBA1 and ALDBA2 schemes for the wider ranges of maximal cycle times and offered loads. From the analysis, it is found that the ALDBA2 scheme provides a wider area of the maximum utilization than the ALDBA1 scheme. The highest bandwidth utilization in the ALDBA2 scheme is 0.9 and it could achieve the same results from the 1.25 to 3-ms cycle times with a lowest offered load of 0.75 while the ALDBA1 scheme could achieve the same result from the 2 to 3-ms cycle times with a lowest offered load of 0.75, as shown using the black arrows in the contour plots. Therefore, the ALDBA2 scheme is more suitable than the ALDBA1 scheme in term of the bandwidth utilization even at the lowest cycle time.

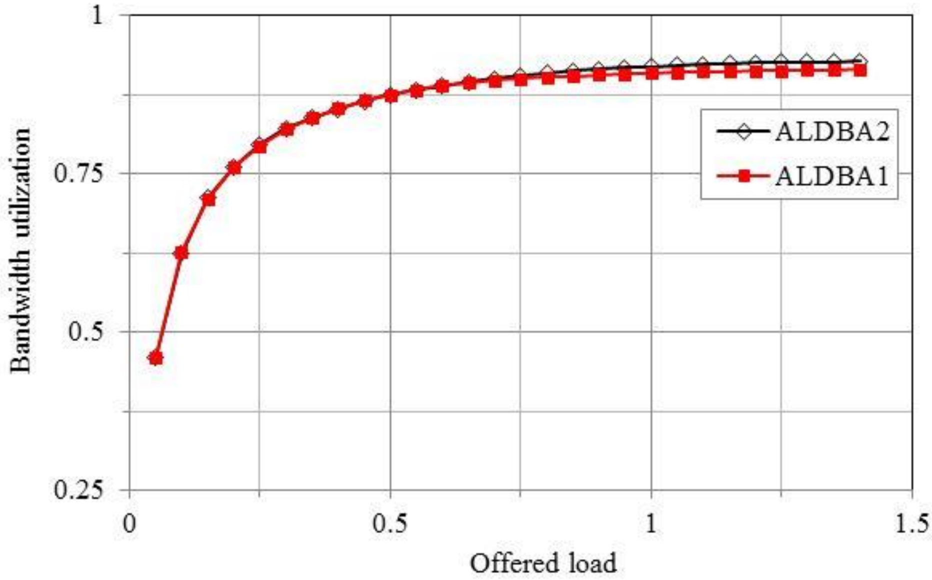


Fig. 5.16 Comparison of bandwidth utilization between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time and $N_{FTTH}:N_{WSN}$ = 8:8.

Figure 5.16 shows a comparison of the bandwidth utilization against the different offered loads between the ALDBA1 and ALDBA2 schemes. The figure shows very close/similar results in both the schemes for a 2-ms cycle time. However, the contour plots in the Figs. 5.15(a) and 5.15(b) provide a clear conception that the ALDBA2 scheme provides better results from the very smaller cycle times.

5.2.3 Upstream Efficiency

Alike the bandwidth utilization the ALDBA2 scheme provides better upstream efficiency than that of the ALDBA1 scheme. The following equation is used for the ALDBA2 scheme to calculate the upstream efficiency UE_{A2}:

$$UE_{A2} = \begin{cases} \dfrac{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred}\right)}{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred} + B_C\right)} & \text{if } W_i^R < W_i^{\max} + W_i^{excess} \\ \dfrac{\sum_{i=1}^{N}\left(W_i^{\max} + W_i^{excess} + W_i^{pred}\right)}{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred} + B_C\right)} & \text{if } W_i^R \geq W_i^{\max} + W_i^{excess} \end{cases} \tag{5.10}$$

Comparison of the upstream efficiencies between the ALDBA1 and ALDBA2 schemes for the same ranges of cycle times and offered loads are shown by the contour plots in Figs. 5.17(a), and 5.17(b), respectively. In this case, the ALDBA2 scheme is also better than the ALDBA1 scheme; this result is consistent with all the above results. However, the highest upstream efficiency area of the ALDBA2 scheme is far larger than that of the ALDBA1 scheme in both the cases of the maximal cycle times and offered loads.

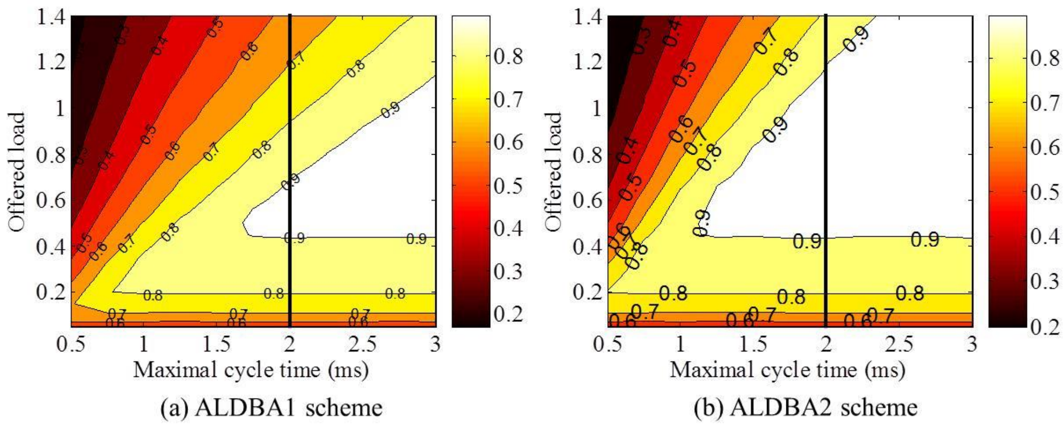


Fig. 5.17 Upstream efficiency in a single-OLT PON-based hybrid networks for the ALDBA1 and ALDBA2 schemes and $N_{FTTH}:N_{WSN}$ = 8:8.

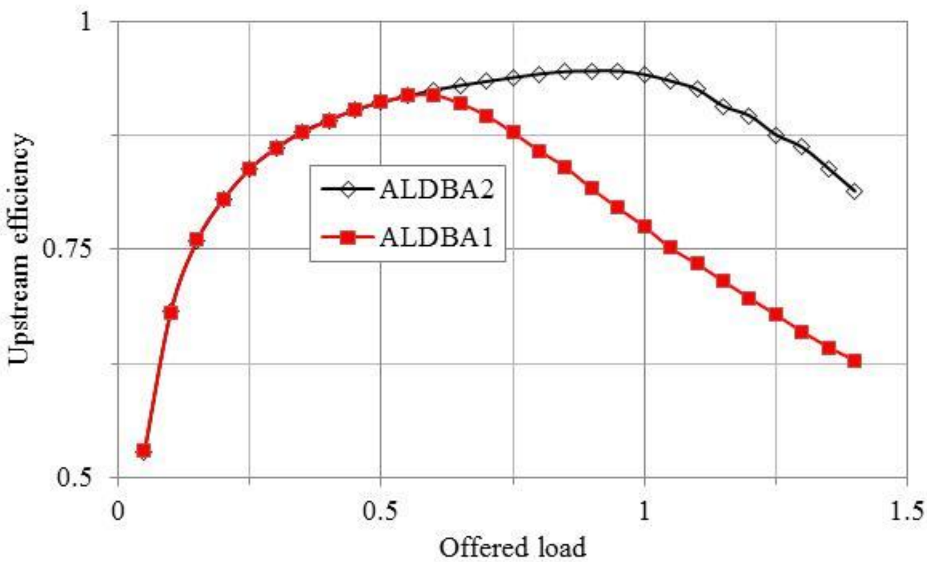


Fig. 5.18 Comparison of upstream efficiency between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time and $N_{FTTH}:N_{WSN}$ = 8:8.

The comparison of the upstream efficiency between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time is shown in Fig. 5.18. This figure shows that the upstream efficiency for the ALDBA1 scheme increase gradually up to an offered load of 0.6 and then decrease up to the highest offered load of 1.4. On the other hand, the upstream efficiency of the ALDBA2 scheme increases until the offered load of 1.0 and then decreases gradually up to the highest offered load of 1.4. However, the upstream efficiency of the ALDBA2 scheme at the highest offered is far larger than that of the ALDBA1 scheme.

5.2.4 Jitter

The following equation is used to calculate the jitter performance for the ALDBA2 scheme of the proposed PON-based hybrid FTTH and WSNs:

$$J_{A2} = \sqrt{\frac{1}{q}\sum_{j=1}^{q}\left(T_{avl,j}^{A2} - T_{avl,j-1}^{A2}\right)^2} \tag{5.11}$$

here, J_{A2} is the jitter in the ALDBA2 scheme, and $T_{avl,j}^{A2}$ is the data arrival time in the ALDBA2 scheme at the time cycle j.

The data packet arrival time $T_{avl,j}^{A2}$ at the time cycle j in the ALDBA2 scheme can be calculated by using the Eq. 5.12:

$$T_{avl,j}^{A2} = \begin{cases} \dfrac{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred} + B_C\right)}{R_U} & \text{if } W_i^R < W_i^{\max} + W_i^{excess} \\ \dfrac{\sum_{i=1}^{N}\left(W_i^{\max} + W_i^{excess} + W_i^{pred} + B_C\right)}{R_U} + T_{cng} & \text{if } W_i^R \geq W_i^{\max} + W_i^{excess} \end{cases} \tag{5.12}$$

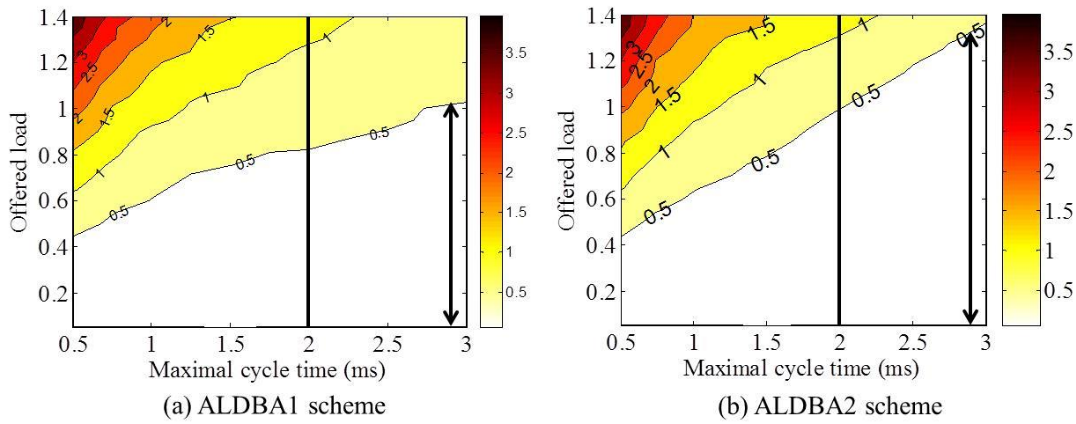


Fig. 5.19 Jitter in a single-OLT PON-based hybrid networks for the ALDBA1 and ALDBA2 schemes and $N_{FTTH}:N_{WSN}$ = 8:8.

Jitter performances of the ALDBA1 and ALDBA2 schemes for a PON-based hybrid FTTH and

WSNs are shown in Figs. 5.19(a), and 5.19(b). As shown using the black arrows in the contour plots, the ALDBA2 scheme provides a wider area of lower jitter than that of the ALDBA1 scheme in both the directions of the maximal cycle times and offered loads. In the ALDBA2 scheme, the lowest jitter of 0.5 ms continues until the offered load of 1.35 at a 3-ms cycle time while the ALDBA1 scheme provides the lowest jitter of 0.5 ms until the offered load of 1.0 at a 3-ms cycle time.

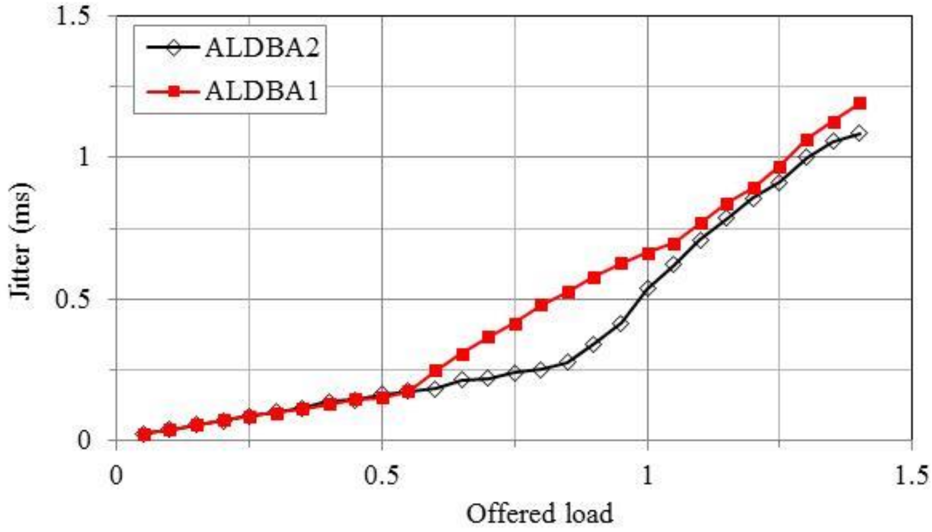


Fig. 5.20 Comparison of jitter between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time and $N_{FTTH}:N_{WSN}$ = 8:8.

From the comparison of the jitter between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time in Fig. 5.20, it is found that the ALDBA2 scheme performs better than the ALDBA1 scheme from the offered load of 0.55 to the offered load of 1.05. In contrast, the ALDBA2 scheme provides similar jitter performances with the ALDBA1 scheme up to the offered load of 0.55 and offered load larger than 1.05.

5.2.5 Throughput

Figures 5.21(a) and 5.21(b) show the contour plots of throughput for the different offered loads and cycle times for the ALDBA1 and ALDBA2 schemes, respectively. Again the ALDBA2 scheme also provides better results in terms of the throughput than the ALDBA1 scheme as all other parameters explained above. From the comparison of the throughput in the figures it is clear that the ALDBA2 scheme provides a wider area of higher throughput than that of the ALDBA1 scheme in both the directions of offered loads and maximal time cycles. This improvement of the throughput is achieved due to the utilization of the excessive bandwidth from the lightly loaded ONUs for the heavily loaded ONUs and average bandwidth savings from the ONUs connected to the CHs of WSN for the deferred data.

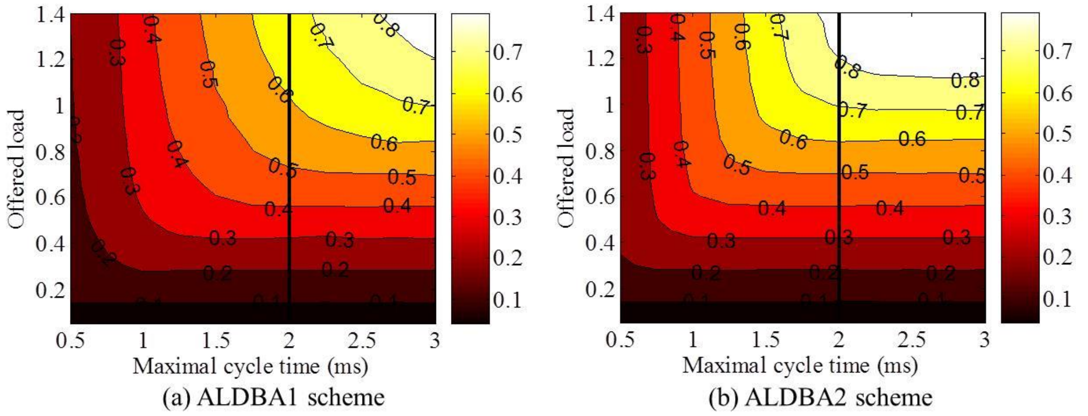


Fig. 5.21 Throughput in a single-OLT PON-based hybrid networks for the ALDBA1 and ALDBA2 schemes and $N_{FTTH}:N_{WSN}$ = 8:8.

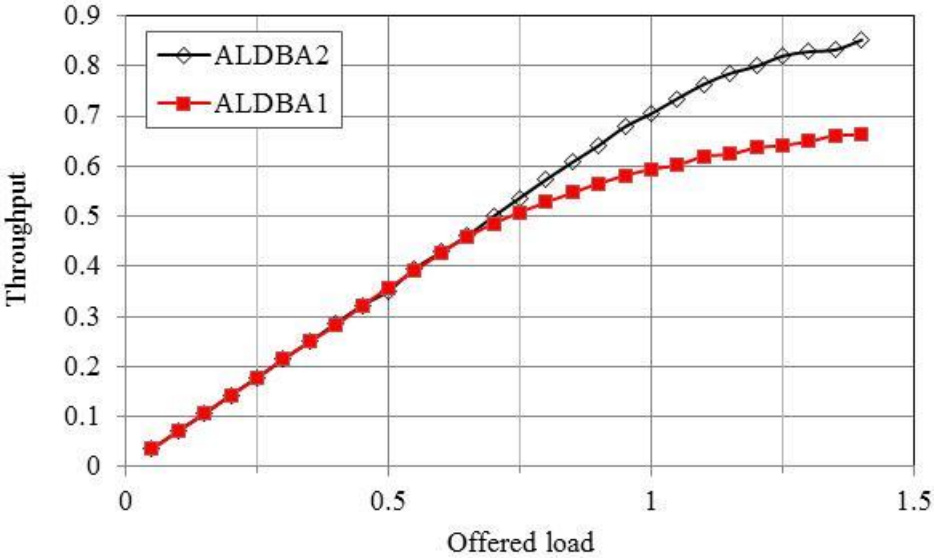


Fig. 5.22 Comparison of throughput between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time and $N_{FTTH}:N_{WSN}$ = 8:8.

Figure 5.22 compares the throughput between the ALDBA1 and ALDBA2 schemes for a 2-ms cycle time and $N_{FTTH}: N_{WSN}$ = 8:8 for a range of offered loads of 0.05-1.4. This figure proves that the ALDBA2 scheme achieves a throughput of more than 85% at an offered load of 1.4 compared to the ALDBA1 scheme achieving that of more than 65% at an offered load of 1.4. However, both the schemes provide the same throughput for the lower offered loads, i.e., offered loads from 0.05 to 0.7. Hence, it can be concluded that in terms of the throughput the ALDBA2 scheme is more effective than the ALDBA1 scheme for the higher offered loads.

The most important principles of a DBA scheme are; to increase the effective bandwidth by decreasing the bandwidth wastage to improve the performances of a PON system. The first reason for the performance enhancement in the ALDBA2 scheme than the ALDBA1 scheme is the utilization of the excess bandwidth for the heavily loaded ONUs that is being wasted in the ALDBA1 scheme. The 2nd reason is the utilization of the average bandwidth savings for the deferred data in the ALDBA2 scheme. But in the ALDBA1 scheme there is no bandwidth for the deferred data as a result the deferred data must be waiting for the next time cycle that increases the delay and reduces the bandwidth utilization.

5.3 Performance Analysis of the ALDBAM Scheme

In this section, the performance of the proposed ALDBAM scheme for a hybrid multi-OLT PON is evaluated in terms of the average packet delay, bandwidth utilization, jitter, upstream efficiency, and throughput. A hybrid PON architecture with two OLTs and 32 ONUs in a tree topology are considered in the analysis. In the ALDBAM scheme, two different maximum transmission windows for the two different service providers in the upstream transmission and two different maximum transmission windows for the two OLTs in the downstream transmission are considered. This scheme is also incorporated to the impact of the guard time savings by fairly distributing to the heavily loaded ONUs. The downstream and upstream channel speeds were considered at 1 Gbps. The distance from an ONU to the OLT is assumed to be random and in the range of 10-20 km. All the data packets were assumed to have the same priority. This traffic model was generated the traffic from 0 to multiple packets in each active ONU in every time cycle, and the total requested window size by an ONU is depended on the number of packets multiplied by the maximum length of a packet, $PB_{FTTH}^{\max}$ for the FTTH terminals and $PB_{WSN}^{\max}$ for the CHs of the WSN. All the analyses were performed for non-uniform offered loads in the range of 0-1.0 with a variable cycle time in the range of 0.5-3.0 ms. The simulation parameters are summarized in Table 5.2.

Table 5.2 Simulation parameters used in the multi-OLT PON-based FTTH and WSN

Symbol	Quantity	Value
N	Total number of ONUs	32
N_{OLT}	Total number of OLTs	2
D	Distance between OLTs and ONUs	10 to 20km
T_{on}	Laser on time	1.5μs
T_{off}	Laser off time	1.5μs
T_{FRTT}	Fluctuation of RTT	1.5μs
T_{CDR}	Clock and data recovery time	0.5μs
T_{cycle}	Cycle times	0.5 to 3.0 ms
T_{proc}	Data processing time	10μs
R_U	Transmission speed	1Gbps
B_R	Length of Report message	576 bits
B_E	Length of Ethernet overhead	304 bits
$B_{FTTH}^{\max}$	Maximum length of an FTTH packet	1500 bytes
$B_{WSN}^{\max}$	Maximum length of a WSN packet	1024 bytes
P	Number of generated packets	0 to 10

This section also compares the system performance of the proposed ALDBAM scheme for a multi-OLT PON-based hybrid networks with that of the ALDBA1 and ALDBA2 schemes for a single-OLT PON-based hybrid networks. All the performance parameters were analyzed for the non-uniform burst traffics in both the upstream and downstream directions.

5.3.1 Delay

One of the main objectives of the proposed ALDBAM scheme for the multi-OLT PON-based hybrid networks is the reduction of the end-to-end packet delay by allocating larger transmission windows to the heavily loaded ONUs from the lightly loaded ONUs and guard time savings. In the ALDBAM scheme of the multi-OLT PON-based hybrid networks, reduction of the packet delay is also achieved by reducing the data processing time in the multiple OLTs, by providing some transmission windows from the average bandwidth savings of the ONUs connected to the CHs of WSN for the predicted data traffics during the waiting time, and guaranteed scheduling of the Gate messages. The following equation is used for the ALDBAM scheme to calculate the end-to-end packet delay in the multi-OLT PON-based hybrid networks:

$$D_{AM} = \begin{cases} \dfrac{\sum_{i=1}^{N}(W_i^R + W_i^{pred\_m} + T_C)}{R_U} & \text{if } W_i^R < W_i^{\max} + W_i^{excess\_m} \\ \dfrac{\sum_{i=1}^{N}(W_i^{\max} + W_i^{excess\_m} + W_i^{pred\_m} + T_C)}{R_U} + T_{cng} & \text{if } W_i^R \geq W_i^{\max} + W_i^{excess\_m} \end{cases} \tag{5.13}$$

here, D_{AM} is the end-to-end packet delay in the ALDBAM scheme, W_i^R is the requested window size by the ONU i, $W_i^{\max}$ is the maximum window size of the ONU i, W_i^{pred-m} is the predicted window for the ONU i in the multi-OLT PON, $W_i^{excess-m}$ is the excess bandwidth for the ONU i from the lightly loaded ONUs, T_C is the summation of the B_R/R_u, B_E/R_u, T_{FRTT}, and T_{CDR}, and T_{cng} is the congestion delay.

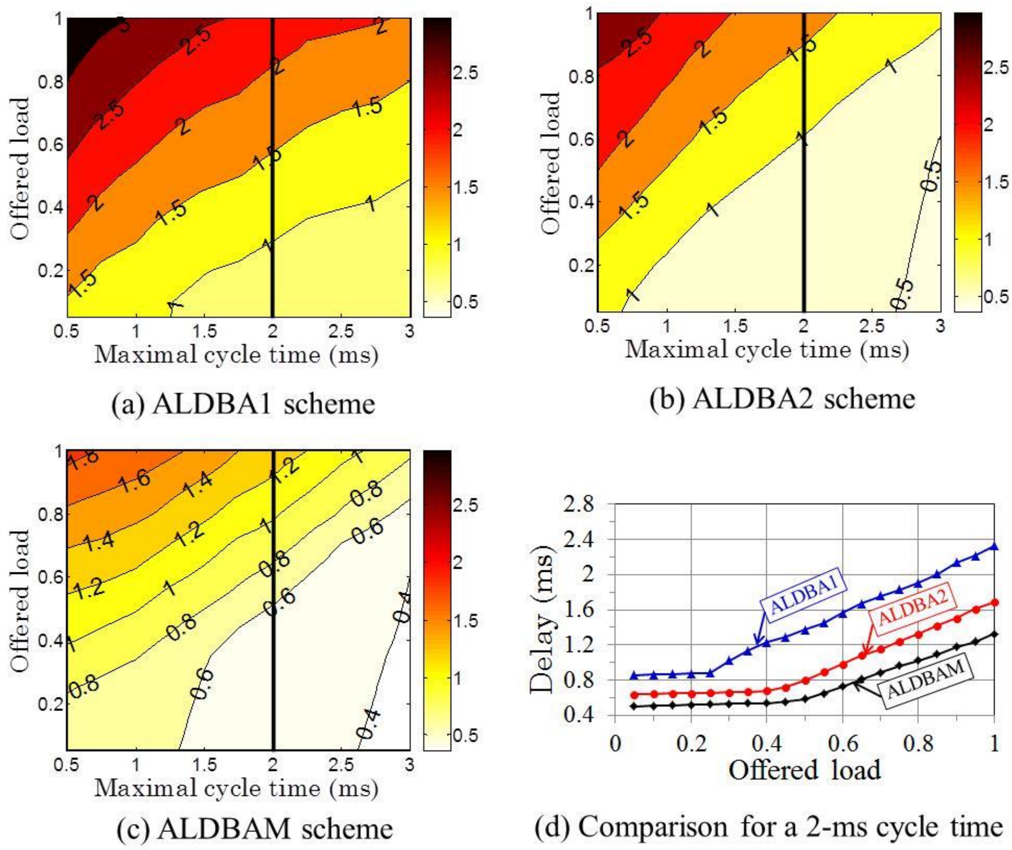
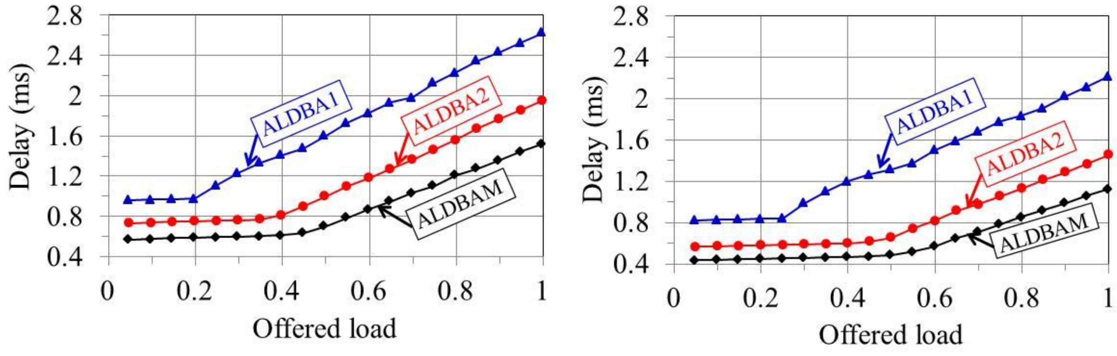


Fig. 5.23 Average packet delay in ms in a PON-based hybrid networks and N_{FTTH}:N_{WSN} = 16:16.

Figures 5.23(a), 5.23(b), and 5.23(c) show the end-to-end average packet delay of the ALDBA1, and ALDBA2 schemes for the single-OLT PON-based hybrid networks, and the ALDBAM scheme for the multi-OLT PON-based hybrid networks, respectively, for N_{FTTH}:N_{WSN} = 16:16 using contour plots for the different offered loads and cycle times. From these three contour plots it can be said that the ALDBAM scheme provides a wider area of the lowest packet delay in both the directions of offered loads and cycle times than both the ALDBA1 and ALDBA2 schemes. On the other hand, the highest packet delay in the ALDBAM scheme is 1.8 ms, whereas the highest packet delays in the ALDBA1 and ALDBA2 schemes are 3 ms and 2.5 ms, respectively. Figure 5.23(d) shows a comparison of the average packet delay among the three schemes for a 2-ms cycle time against a range of offered loads of 0.05 to 1.0. The ALDBAM scheme provides approximately 75% and 30% less delay than the ALDBA1 and ALDBA2 schemes, respectively, at an offered load of 1.0. However, the effectiveness of the ALDBAM scheme becomes more significant at higher data rates and larger number of service providers and OLTs.



(a) $N_{FTTH} : N_{WSN} = 24{:}8$ (b) $N_{FTTH} : N_{WSN} = 8{:}24$

Fig. 5.24 Comparison of average packet delay among the ALDBA1, ALDBA2, and ALDBAM schemes for a 2-ms cycle time.

Figures 5.24(a) and 5.24(b) compare the average packet delay among the ALDBA1, ALDBA2, and ALDBAM schemes for a 2-ms cycle time by changing the ratio of the number of ONUs connected to the FTTH terminals and CHs of the WSN. The delay characteristics of the three schemes in Figs. 5.24(a) and 5.24(b) are also similar to those in Fig. 5.23(d). However, the average packet delays for all the three schemes are far less when the number of ONUs connected to the CHs of the WSN is larger than those connected to the FTTH terminals, as shown in the Fig. 5.24(b), where $N_{FTTH}{:}N_{WSN}$ = 8:24. The first reason is that a larger number of ONUs from the WSN provide less aggregated traffic in the network as the data rate is lowered, and the packet size is smaller than those of the FTTH terminals. The second reason is that a larger number of ONUs from the WSN provide more bandwidth savings that is utilized by the deferred data.

5.3.2 Bandwidth Utilization

The bandwidth utilization BWU_M of a multi-OLT PON using the ALDBAM scheme is expressed by the Eq. 5.14:

$$BWU_M = \frac{N_{FTTH} G_{OLT1} + N_{WSN} G_{OLT2}}{N_{FTTH} G_{OLT1} + N_{WSN} G_{OLT2} + NT_C} \tag{5.14}$$

here, N_{FTTH} is the number of ONUs connected to the FTTH terminals, N_{WSN} is the number of ONUs connected to the CHs of the WSN, G_{OLT1} is the granted windows by the OLT1, G_{OLT2} is the granted windows by the OLT2, and N is the total number of ONUs in the network.

The proposed ALDBAM scheme can achieve better bandwidth utilization by utilizing both the excessive bandwidth from the lightly loaded ONUs and the guard time savings for the heavily loaded ONUs. The following equation is used for the ALDBAM scheme to calculate the bandwidth utilization BWU_{AM}:

$$
BWU_{AM} = \begin{cases} \dfrac{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred\_m}\right)}{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred\_m} + T_C\right)} & \text{if } W_i^R < W_i^{\max} + W_i^{excess\_m} \\ \dfrac{\sum_{i=1}^{N}\left(W_i^{\max} + W_i^{excess\_m} + W_i^{pred\_m}\right)}{\sum_{i=1}^{N}\left(W_i^{\max} + W_i^{excess\_m} + W_i^{pred\_m} + T_C\right)} & \text{if } W_i^R \geq W_i^{\max} + W_i^{excess\_m} \end{cases} \tag{5.15}
$$

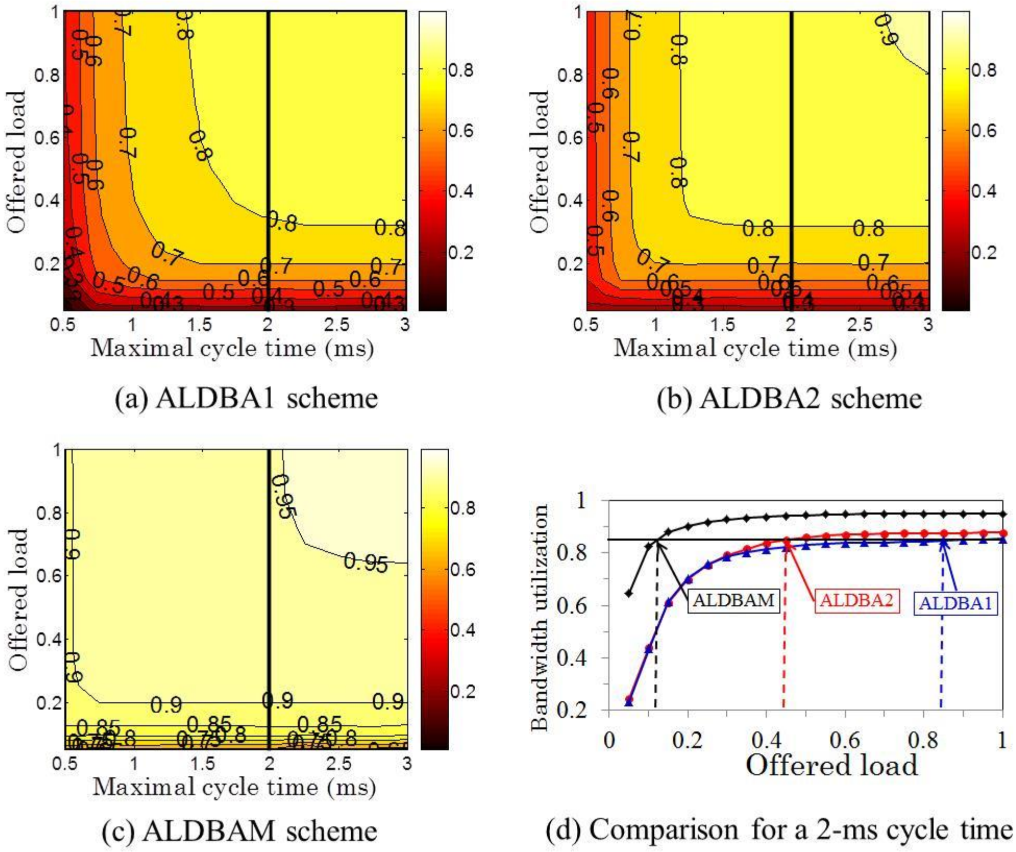
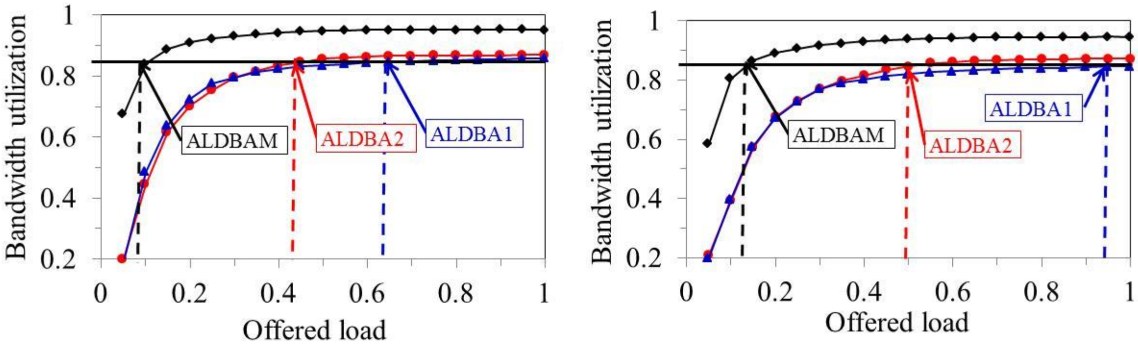


Fig. 5.25 Bandwidth utilization in a PON-based hybrid networks and N_{FTTH}:N_{WSN} = 16:16.

The contour plots of Figs. 5.25(a), 5.25(b), and 5.25(c) show the bandwidth utilization of the ALDBA1, ALDBA2, and ALDBAM schemes, respectively. From the analysis of these three contour plots, it is clear that the ALDBAM scheme provides far superior bandwidth utilization than both the ALDBA1 and ALDBA2 schemes. The highest bandwidth utilization in the ALDBAM scheme is 0.95. In contrast, the highest bandwidth utilization in the ALDBA1 and ALDBA2 schemes is 0.8 and 0.9, respectively. Moreover, the ALDBAM scheme provides higher bandwidth utilization from a much lower value of the offered load. From the comparison of the bandwidth utilization at a 2-ms cycle time in Fig. 5.25(d), the bandwidth utilization in the ALDBAM scheme exceeds 0.85 at an offered load of 0.12. In contrast, the bandwidth utilization exceeds 0.85 at an offered load of 0.45 in the ALDBA2 scheme and at an offered load of 0.85 in the ALDBA1 scheme.



(a) $N_{FTTH} : N_{WSN} = 24{:}8$ (b) $N_{FTTH} : N_{WSN} = 8{:}24$

Fig. 5.26 Comparison of bandwidth utilization among the ALDBA1, ALDBA2, and ALDBAM schemes for a 2-ms cycle time.

Similarly, Figs. 5.26(a) and 5.26(b) compare the bandwidth utilization among the ALDBA1, ALDBA2, and ALDBAM schemes for a 2-ms cycle time by changing the ratio of the number of ONUs connected to the FTTH terminals and the CHs of WSN. If horizontal lines are drawn at a bandwidth utilization of 0.85 in both of the figures, as shown in the Figs. 5.26(a) and 5.26(b), it can be seen that the ALDBAM scheme continually provides similar performance for the different ratios of the number of ONUs connected to the FTTH and WSNs.

5.3.3 Upstream Efficiency

The ratio between the successful upstream transmission and the total generated traffics in the network is called the upstream efficiency. The expression for the upstream efficiency of a PON system is:

$$UE_M = \frac{N_{FTTH} G_{OLT1} + N_{WSN} G_{OLT2}}{N_{FTTH} PB_{FTTH}^{\max} + N_{WSN} PB_{WSN}^{\max} + NT_C} \tag{5.16}$$

where, UE_M is the upstream efficiency in a multi-OLT PON.

The following equation is used for the ALDBAM scheme to calculate the upstream efficiency UE_{AM}:

$$UE_{AM} = \begin{cases} \dfrac{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred\_m}\right)}{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred\_m} + T_C\right)} & \text{if } W_i^R < W_i^{\max} + W_i^{excess\_m} \\ \dfrac{\sum_{i=1}^{N}\left(W_i^{\max} + W_i^{excess\_m} + W_i^{pred\_m}\right)}{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred\_m} + T_C\right)} & \text{if } W_i^R \geq W_i^{\max} + W_i^{excess} \end{cases} \tag{5.17}$$

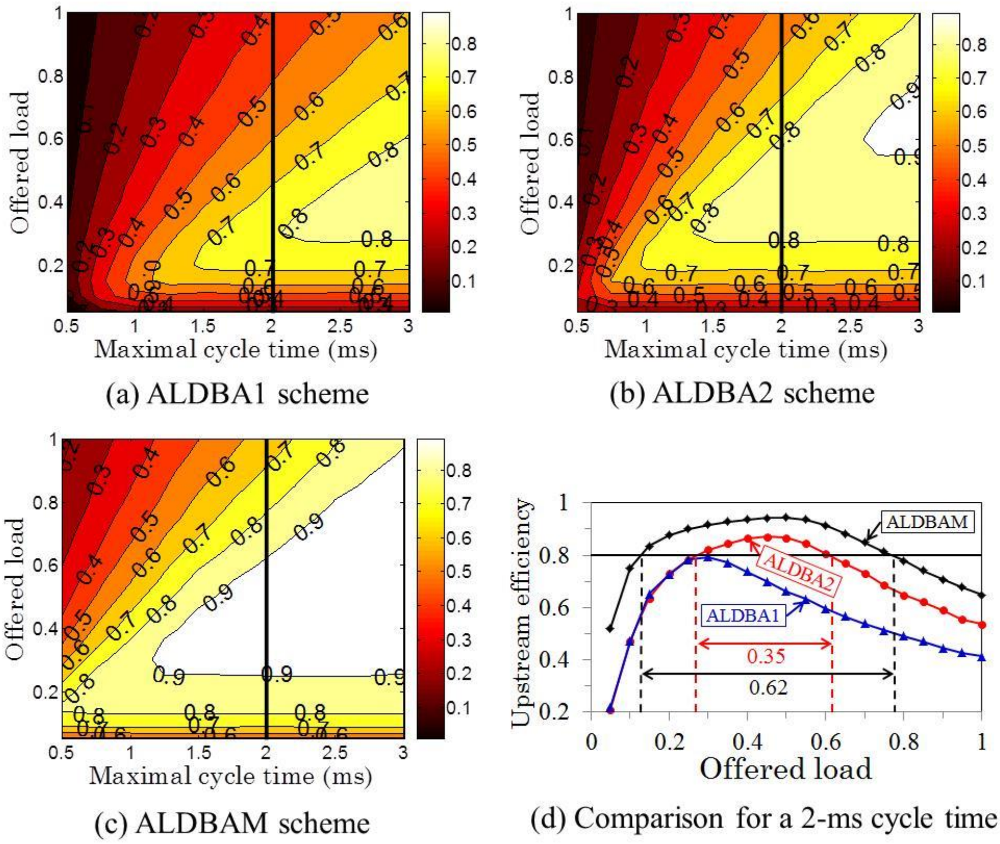
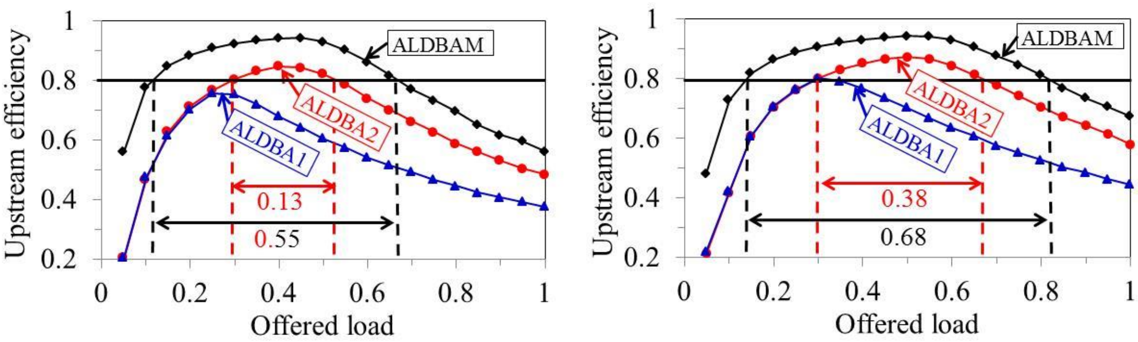


Fig. 5.27 Upstream efficiency in a PON-based hybrid networks and N_{FTTH}:N_{WSN} = 16:16.

Upstream efficiencies are compared among the three schemes by the contour plots in Figs. 5.27(a), 5.27(b), and 5.27(c). In this case, the proposed ALDBAM scheme provides better upstream efficiency than the ALDBA1 and ALDBA2 schemes. The highest upstream efficiency area in the ALDBAM scheme is broadened in both the directions of maximal cycle times and offered loads. This means that the ALDBAM scheme can provide better performance from a lower offered load and cycle time to a higher offered load and cycle time. From the analysis of Figs. 5.27(d), 5.28(a), and 5.28(b), it can be said that the ALDBAM scheme is also consistent for maintaining the higher upstream efficiency for every combination of the number of ONUs from the two different service providers.



(a) $N_{FTTH} : N_{WSN} = 24{:}8$ (b) $N_{FTTH} : N_{WSN} = 8{:}24$

Fig. 5.28 Comparison of bandwidth utilization among the ALDBA1, ALDBA2, and ALDBAM schemes for a 2-ms cycle time.

Figures 5.27(d), 5.28(a) and 5.28(b) compare the upstream efficiency among the ALDBA1, ALDBA2, and ALDBAM schemes for N_{FTTH}:N_{WSN} = 16:16, N_{FTTH}:N_{WSN} = 24:8, and N_{FTTH}:N_{WSN} = 8:24, respectively. To compare the results of the upstream efficiency among the three schemes more efficiently, horizontal lines are drawn at the 80% upstream efficiency level in the Figs. 5.27(d), 5.28(a), and 5.28(b). From these three figures, it is clear that the ALDBAM scheme provides about two times more offered loads than the ALDBA2 scheme for both the cases of N_{FTTH}:N_{WSN} = 16:16 and N_{FTTH}:N_{WSN} = 8:24 with an upstream efficiency higher than 80%. Moreover, the ALDBAM scheme provides four times more offered load than the ALDBA2 scheme for the N_{FTTH}:N_{WSN} = 24:8 case with an upstream efficiency higher than 80%. However, the ALDBA1 scheme never provides the upstream efficiency higher than 80%.

5.3.4 Jitter

The burst network traffics and the DBA scheme in a PON provide variation in the T_{cycle} in every time cycle. Owing to this variation in the T_{cycle}, the arrival times of data packets fluctuate in different time cycles. To measure the variation in the data packet arrival times, the jitter performance of the proposed ALDBAM scheme is analyzed. The jitter may be calculated by the following equations:

$$J_{AM} = \frac{1}{n}\sqrt{\sum\left(T_{avl,j}^{AM} - T_{avl,j-1}^{AM}\right)^2} \qquad (5.18)$$

$$T_{avl,j}^{AM} = \begin{cases} \dfrac{\sum_{i=1}^{N}\left(W_i^R + W_i^{pred\_m} + T_C\right)}{R_U} & \text{if } W_i^R < W_i^{\max} + W_i^{excess\_m} \\ \dfrac{\sum_{i=1}^{N}\left(W_i^{\max} + W_i^{excess\_m} + W_i^{pred\_m} + T_C\right)}{R_U} + T_{cng} & \text{if } W_i^R \ge W_i^{\max} + W_i^{excess\_m} \end{cases} \qquad (5.19)$$

where, J_{AM} is the jitter in the ALDBAM scheme, n is the total number of time cycles, $T^{AM}_{avl,j}$ is the data packets' arrival time in the multi-OLT PON at the time cycle j, and j = 1, 2, 3 … n.

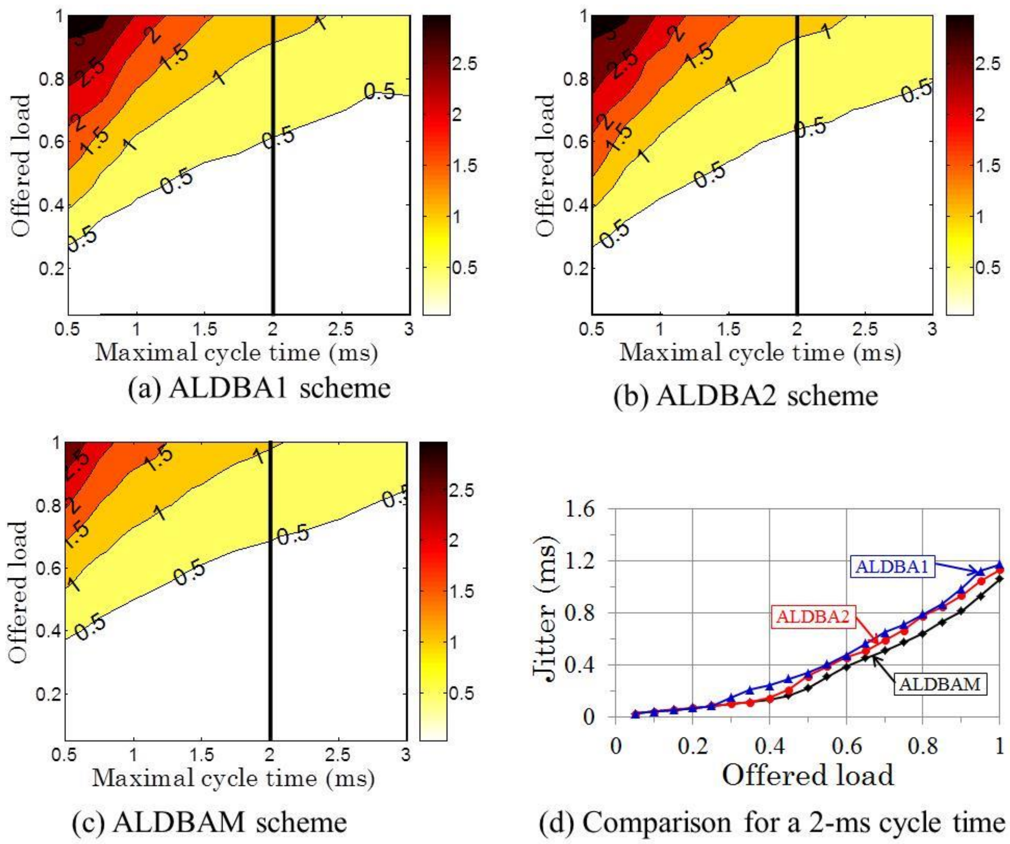
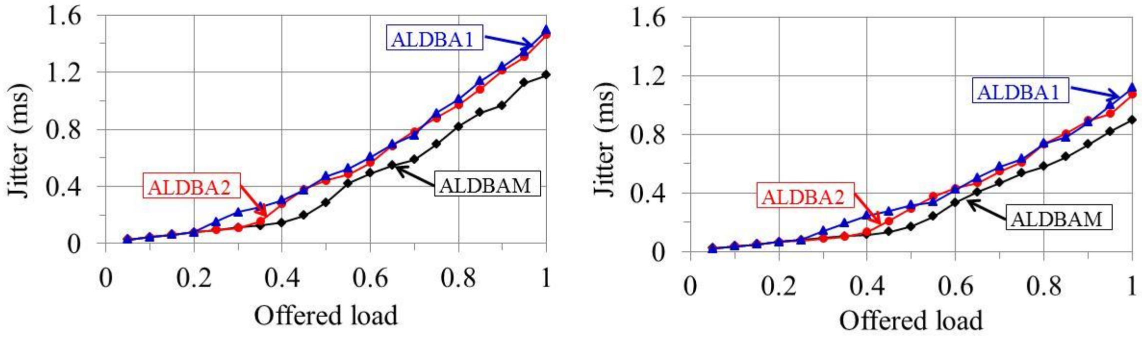


Fig. 5.29 Jitter in a PON-based hybrid networks and N_{FTTH}:N_{WSN} = 16:16.

Usually, in a DBA scheme, jitter cannot be avoided because of the bursty nature of the network traffics. The contour plots in Fig. 5.29 show the jitter performance of the ALDBA1, ALDBA2, and ALDBAM schemes. From the contour plots, it is clear that the ALDBAM scheme provides less jitter than the ALDBA1 and ALDBA2 schemes in both the directions of maximal cycle times and offered loads. The comparison of the jitter for a 2-ms cycle time is shown in Fig. 5.29(d). In this figure it is clear that the jitter in the ALDBAM scheme is similar to that of the ALDBA1 and ALDBA2 schemes at the lower offered loads. However, the ALDBAM scheme provides little bit lower jitter than the ALDBA1 and ALDBA2 schemes at the higher offered loads.



(a) $N_{FTTH} : N_{WSN} = 24:8$ (b) $N_{FTTH} : N_{WSN} = 8:24$

Fig. 5.30 Comparison of jitter among the ALDBA1, ALDBA2, and ALDBAM schemes for a 2-ms cycle time.

Figures 5.30(a) and 5.30(b) show the comparison of the jitter in ms among the ALDBA1, ALDBA2, and ALDBAM schemes against the offered loads with a different number of ONUs from the two service providers. The jitter characteristics at a 2-ms cycle time for every combination of ONUs from the FTTH terminals and WSN are similar in all the three schemes. However, the larger number of ONUs connected to the CHs of WSN, as shown in the Fig. 5.30(b), provides lower jitter in every scheme than other two cases in the Figs. 5.29(d) and 5.30(a).

5.3.5 Throughput

Finally, the improvement in throughput is compared when the ALDBAM scheme is used in a hybrid multi-OLT PON. Figures 5.31(a), 5.31(b), and 5.31(c) show the contour plots of the throughput for the different offered loads and cycle times for the ALDBA1 and ALDBA2 schemes in a single-OLT PON-based hybrid networks, and the proposed ALDBAM scheme in a multi-OLT PON-based hybrid networks, respectively. As expected, the ALDBA1 scheme has the lowest throughput, and the maximum throughput achieved in the ALDBA1 scheme as shown in the contour plot in the Fig. 5.31(a) is 0.6. On the other hand, the maximum throughput achieved by the ALDBA2 scheme is 0.8, as shown in the contour plot in the Fig. 5.31(b). Ultimately, the ALDBAM scheme achieves the highest throughput of 0.9 as shown in the Fig. 5.31(c). The main reason for the lowest throughput in the ALDBA1 scheme is less utilization of the upstream channel due to the lightly loaded ONUs, whereas the ALDBAM scheme gains the utilization of excess bandwidth from the lightly loaded ONUs and guard time savings for the heavily loaded ONUs. From the comparison of the throughputs among the three schemes for a 2-ms cycle time, the ALDBAM scheme achieved more than 15% and 35% higher throughput than the ALDBA2 and ALDBA1 schemes, respectively, for the every case of the ratio of ONUs from the two different service providers, as shown in the Figs. 5.31(d), 5.32(a), and 5.32(b).

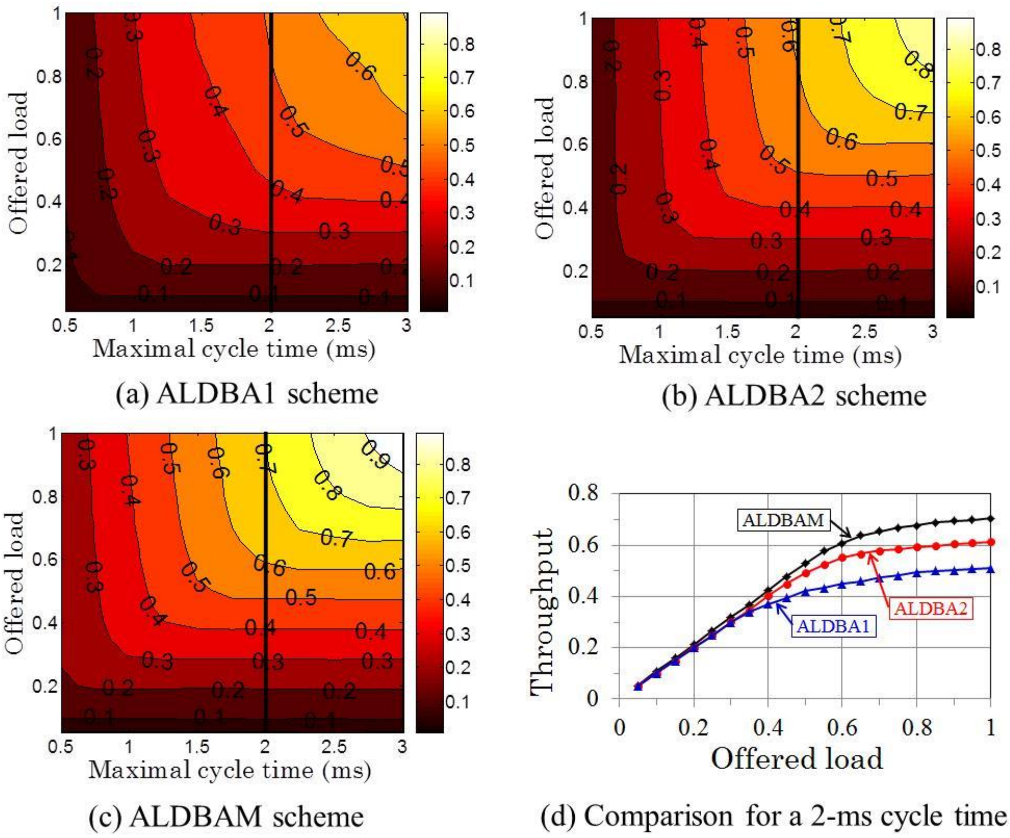


Fig. 5.31 Throughput in a PON-based hybrid networks and N_{FTTH}: N_{WSN} = 16:16.

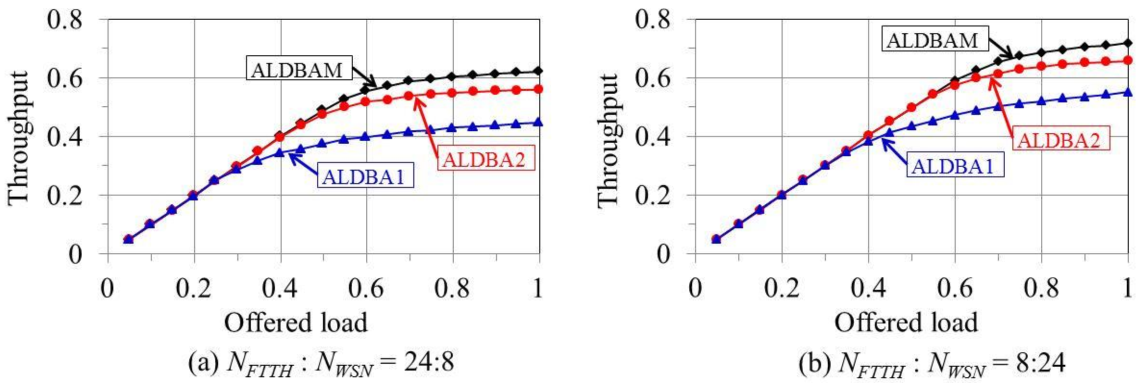


Fig. 5.32 Comparison of throughput among the ALDBA1, ALDBA2, and ALDBAM schemes for a 2-ms cycle time.

From the analyses of all the results in this chapter it is clear that even though the ALDBA2 scheme can achieve better results in a single-OLT PON-based hybrid networks than the ALDBA1 and the conventional LS schemes, it still has its limitations because the ALDBA2 scheme does not consider the utilization of the guard time savings in a multi-OLT PON-based hybrid networks. In a multi-OLT PON-based hybrid networks, the computation time for data packet processing in the OLT is also reduced by dividing the upstream traffic from the ONUs of the different service providers to the multiple OLTs. The proposed ALDBAM scheme copes with all the limitations of the ALDBA1 and ALDBA2 schemes and provides enhanced performances. Moreover, the effectiveness of the proposed ALDBAM scheme will be more significant if the analyses are repeated for a larger number of OLTs and service providers.

5.4 Comparisons Among the LS, EBR, ALDBA1, ALDBA2, and ALDBAM Schemes

Many DBA algorithms have been developed for the PON-based access networks to provide higher bandwidth utilization and QoSs. However, it is very difficult to select the best DBA algorithm to compare with the proposed DBA algorithms in this thesis because this thesis provides several DBA algorithms specially for the hybrid network architectures of the PON comprising the FTTH and WSNs while all the existing DBA algorithms are designed only for the FTTH network. The difficulties are matching the simulation environments, network architectures, logical operations, and considering the data classes among the existing and proposed DBA schemes. For example, all the existing DBA schemes are considered for the data traffics from the FTTH access network but in the proposed schemes two different service providers, FTTH and WSNs, are considered. In the existing EBR scheme, ONUs are divided into two groups, lightly loaded and heavily loaded ONUs, which is similar to the proposed ALDBA2 and ALDBAM schemes but the probability of getting more lightly loaded ONUs in the ALDBA2 and ALDBAM schemes is higher than the EBR scheme because the WSN generates very less traffic. That is why comparing the performance among the EBR, ALDBA2, and ALDBAM schemes are not fair as the EBR scheme considers only the FTTH access networks while the ALDBA2 and ALDBAM schemes considers both the FTTH and WSNs. In the existing LSTP scheme, deferred data are considered in allocating the transmission windows to the ONUs as the proposed ALDBA2 and ALDBAM schemes. However, the LSTP scheme does not provide any explanation from where the additional bandwidth will be provided for the deferred data while both the ALDBA2 and ALDBAM schemes provide this additional bandwidth from the average bandwidth savings due to the ONUs connected to the WSNs. In this context, it is also not fair to compare the performances among the LSTP, ALDBA2, and ALDBAM schemes. Moreover, all the DBA algorithms proposed in this thesis deal with the different lengths of data packets of different service providers and considered individual maximum transmission window for every service provider depending on their maximum packet lengths while a single maximum transmission window is used for all the existing DBA schemes.

This section compares the two existing DBA algorithms, LS and EBR schemes, and the three proposed DBA algorithms, ALDBA1, ALDBA2, and ALDBAM schemes. The LS scheme is a very basic DBA algorithm and most of the latest DBA schemes provide a little modification of this basic LS DBA scheme. That is why, it is very easy and fair to compare any new DBA algorithm to the LS scheme and this thesis elaborately compares the performances of the proposed DBA schemes with those of the LS scheme in the previous sections of this chapter by using simulation results. The EBR scheme also provides a little close relationship with the proposed ALDBA2 and ALDBAM schemes without taking into consideration of the priority scheduling among the different service classes of data packets. However, the basic difference between the ALDBA2 and EBR schemes is that the ALDBA2 scheme considers multiple maximum transmission windows for the multiple service providers in the network and provides some transmission windows for the deferred data while the EBR scheme only considers a single maximum transmission window for the FTTH network. In addition to the consideration of the multiple maximum transmission windows and deferred data, the ALDBAM scheme also uses the multiple OLTs for the multiple service providers in the network to reduce the computational complexity of data packet processing for the data packets from the multiple service providers in a single OLT and to reduce the guard time between every two sequential ONUs. It is clear that comparing the existing EBR scheme with the proposed schemes are not fair as explained above. However, a macro view of comparison is given by considering the same data class for all the schemes. Where, a single-OLT PON and a single service provider is considered for the LS and EBR schemes while two service providers in the single-OLT PON are considered for the ALDBA1 and ALDBA2 schemes and two OLTs and two service providers are considered for the ALDBAM scheme. Due to the consideration of the two OLTs for the two service providers the guard intervals and data processing complexity can be reduced in the ALDBAM scheme than that of the LS, EBR, ALDBA1, and ALDBA2 schemes. In addition, providing some transmission windows for the deferred data in the ALDBA2 and ALDBAM schemes reduce the data waiting times in the queue as well as overall delays than the LS, EBR, and ALDBA1 schemes. The EBR, ALDBA2 and ALDBAM schemes require more computational complexity than the LS and ALDBA1 schemes because in the EBR, ALDBA2, and ALDBAM schemes need to calculate the lightly loaded and heavily loaded ONUs. Moreover, the EBR scheme requires differentiation among the data classes of three service classes and the ALDBAM scheme requires sharing of a single polling table and deployment of the multiple OLTs those are significant for increasing difficulties in these two schemes.

Table 5.3 shows a brief comparison among the LS, EBR, ALDBA1, ALDBA2, and ALDBAM schemes. All the numerical values in the Table 5.3 represent for a 2-ms cycle time, 32 ONUs, maximum offered load of 1.0, and data policy for all the schemes were FIFO that means no priority scheduling was considered even for the EBR scheme. Here, the LS and EBR schemes were used for a single-OLT PON connected with a single service provider, i.e., FTTH access terminals, the ALDBA1 and ALDBA2 schemes were used for a single-OLT PON connected with the two different service providers, i.e., FTTH access terminals and CHs of WSN, and the ALDBAM scheme was used for a multi-OLT PON connected with two different service providers, i.e., FTTH access terminals and CHs of WSN, and two OLTs.

Table 5.3 Comparisons among the LS, EBR, ALDBA1, ALDBA2, and ALDBAM schemes

Quantity	LS	EBR	ALDBA1	ALDBA2	ALDBAM
Number of OLTs	One	One	One	One	Multiple
Number of service providers	One	One	Multiple	Multiple	Multiple
Complexity	Low	High	Medium	High	High
Number of mathematical operations	N*2	N*8	N*4	N*6	N*7
Average packet delay in ms	2.83	2.17	2.33	1.69	1.32
Bandwidth utilization	0.83	0.87	0.85	0.88	0.95
Upstream efficiency	0.36	0.44	0.41	0.54	0.65
Jitter in ms	1.63	1.58	1.18	1.14	1.06
Throughput in Gbps	0.43	0.53	0.51	0.61	0.70

5.5 Conclusions

In this chapter, performances of the proposed three DBA algorithms, ALDBA1, ALDBA2, and ALDBAM, for the hybrid PON-based FTTH and WSNs have been numerically analyzed in terms of the average packet delay, bandwidth utilization, upstream efficiency, jitter, and throughput. All the analyses were done for a range of non-uniform traffic loads and cycle times. The main intention over the proposed DBA algorithms for the PON-based FTTH and WSN are to increase the bandwidth sharing efficiency by using individual maximum transmission windows for each service provider. Moreover, the ALDBAM scheme uses the multiple OLTs for independently handling the data packets from the multiple service providers in a u-City to reduce the computational complexity of data packet processing.

The simulation results demonstrate that the proposed ALDBA1 scheme enhances the performances and QoSs of the proposed single-OLT PON-based hybrid networks than those of the conventional LS scheme. However, the ALDBA2 scheme outperformed both the ALDBA1 and LS schemes by utilizing the excess bandwidth savings from the lightly loaded ONUs. When compared with the LS and ALDBA1 schemes, the ALDBA2 scheme provided about 60% and 35% less delay than the LS and ALDBA1 schemes, respectively, for a 2-ms cycle time at an offered load of 1.0. With regard to the bandwidth utilization and jitter, the proposed ALDBA2 scheme provided performance close to but slightly better than those of the LS and ALDBA1 schemes at a 2-ms cycle time. However, the ALDBA2 scheme provided about 18% and 30% more upstream efficiency than the ALDBA1 and LS schemes, respectively, for a 2-ms cycle time at an offered load of 1.0. Moreover, the ALDBA2 scheme provided a wider area of better performance than the LS and ALDBA1 schemes for both the cycle time and offered load, as shown in the figures by using the contour plots, when used with the hybrid PON in each simulation.

The proposed ALDBAM scheme enhances the performance of a multi-OLT PON. Here, both the ALDBAM scheme and the multi-OLT PON-based network architectures are equally important for enhancing all the performances. The multi-OLT PON architecture provides bandwidth savings by the reduction of data processing time, proper guard time management, and perfect scheduling algorithm of the Gate messages from the multiple OLTs. Moreover, the ALDBAM scheme fairly distributes all the bandwidth savings by the multi-OLT PON architecture and the excess bandwidth from the lightly loaded ONUs to the heavily loaded ONUs. The proposed ALDBAM scheme outperformed the LS, ALDBA1, and ALDBA2 schemes in terms of the average packet delay, bandwidth utilization, jitter, upstream efficiency, and throughput. The main contribution of the proposed ALDBAM scheme is that it can provide better bandwidth sharing efficiency and utilization owing to smaller cycle times and lower offered loads. The ALDBAM scheme utilizes guard time savings in a multi-OLT PON and provides better QoSs than the ALDBA1 and ALDBA2 schemes. The ALDBAM scheme provided

115% less delay with 40% higher throughput, 75% less delay with 35% higher throughput, and 30% less delay with 15% higher throughput for a 2-ms cycle time at an offered load of 1.0 when compared with the LS, ALDBA1, and ALDBA2 schemes, respectively.

From the discussions in this chapter, it is shown that all the performances have been improved by deploying two OLTs for the two service providers in the ALDBAM scheme and it is being the best among the proposed schemes. Furthermore, it can be said that the differences of the better performances between the single-OLT and multi-OLT PONs will be more significant for a larger number of service providers and OLTs. However, the difficulties and complexities of a sharing polling table, the installation cost of more OLTs, and the network complexity for adding several service providers with different features in a PON are the limiting factors in the multi-OLT PON and the ALDBAM scheme. That is why, it is difficult to mention about the optimum number of service providers and OLTs in a multi-OLT PON-based hybrid network. A trade-off analysis between the advantages and difficulties of the multi-OLT PON is required for determining the optimum numbers of service providers and OLTs.

6. Architectures of PON-Based Open Access Networks

This chapter presents two different network architectures of the proposed PON-based open access networks (OANs). In the 1st section of this chapter, a brief definition of an OAN is given. In the 2nd and 3rd sections of this chapter, the proposed architectures of a multi-OLT PON-based OAN (M-OAN), and a multi-OLT and multi-wavelength PON-based OAN (MM-OAN) are explained, respectively. In the M-OAN, a single wavelength is considered for all the service providers in both the upstream and downstream directions. In the MM-OAN, a single wavelength in the downstream direction and multiple wavelengths in the upstream direction for the multiple service providers are considered.

6.1 Open Access Networks (OANs)

One of the most used definitions of an OAN is that it is a network where multiple service providers can use the network simultaneously. The OAN is also a network that is open to any service provider, local or otherwise, and can use it to offer different services to the subscribers. The service providers are able to offer any number of services and the subscribers are also able to choose any service provider for each of the services those they choose to subscribe to. The OAN model [72], in which services are provided on a fair and non-discriminatory basis to the network users, is enabled by conceptually separating the roles of the service provider and the network operator or owner. Due to the different technical and economic natures of the different parts of the network, different roles and actors can be identified. The OAN has the following key features [73]:

- It has a true broadband capacity.
- This network is a common public utility for the information society. The OAN is intended to be used by any party located within the community it serves, e.g., public and private, business, and residential.
- The OAN is owned and controlled independently by any service or content which runs over it. This affords anyone connected to the network to take or provide content or service from or to anyone they choose.

Moreover, the OAN is a cheap and available to the end users for a broadband solution because the deployment cost of the networks may be recovered from the multiple service providers [74]. Figure 6.1 shows a basic diagram of an OAN. Here, the users 1, 2 … N is directly connected to a single backbone network and the service providers 1, 2, … m is connected to that single network through a data link layer equipment of each service provider. The *m* different service providers use *m* COs and data link layer equipment where every ONU is shared by the users of all the service providers.

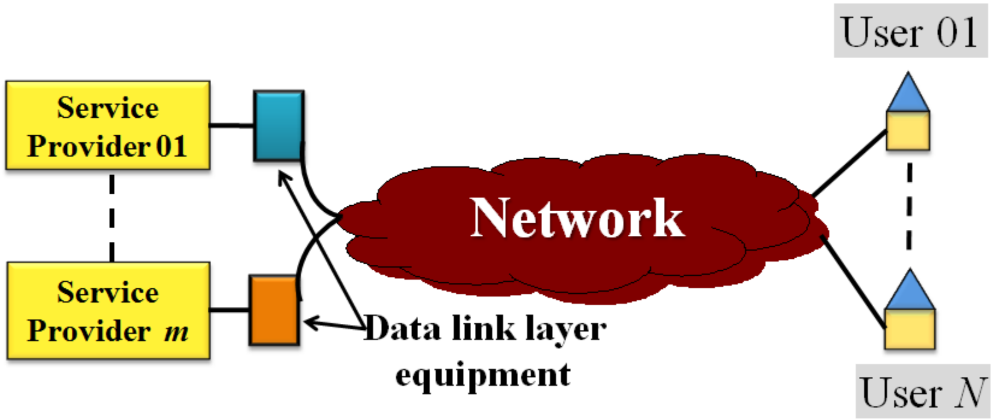


Fig. 6.1 Basic diagram of an open access network.

6.2 Single-OLT PON-Based OAN (S-OAN)

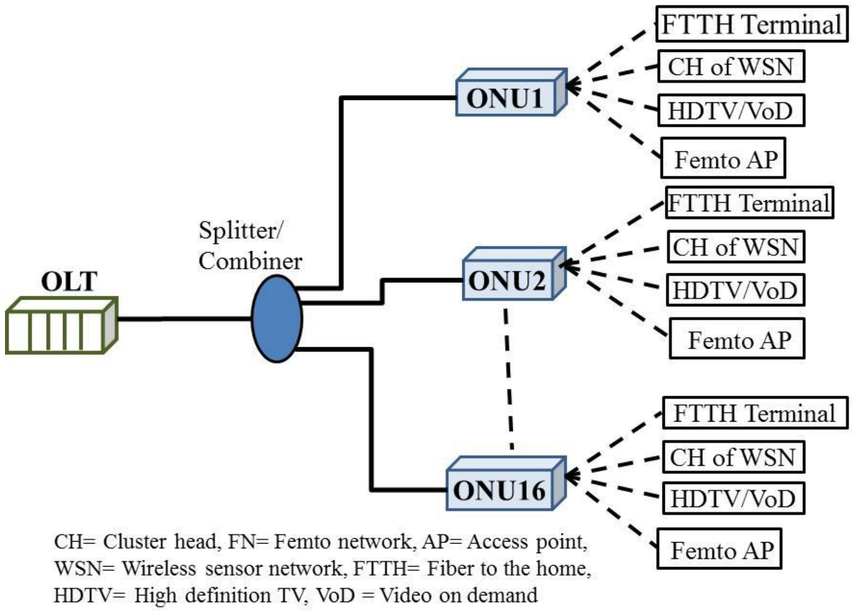


Fig. 6.2 Architecture of a single-OLT PON-based OAN.

Figure 6.2 shows a diagram of an S-OAN. Here, each ONU is shared by the four service providers communicating with a single OLT at the CO of the OAN. In the upstream direction of the S-OAN, each ONU transmits the data packets from all the service providers connected to that ONU. The number of service providers connected to an ONU is random. That means the number of service providers connected to an ONU varies from 1 to *m*. In the downstream direction of the S-OAN, every ONU accepts the broadcasted data packets for every service provider from the OLT.

6.3 Multi-OLT PON-Based OAN (M-OAN)

A PON also has sufficient bandwidth to achieve the required bandwidth demand of an OAN. However, the current PON architecture with a single OLT is not efficient enough to integrate all the service providers in an OAN [16]. In the chapter 3 of this thesis, a multi-OLT PON structure has been proposed for combining the FTTH and WSNs in a single optical network [18,19,20]. However, the multi-OLT PON structure is not suitable for an OAN as in the multi-OLT PON an ONU is considered as an access terminal only for a single service provider, i.e., FTTH network or WSNs, but in an OAN every access terminal is shared by all the service providers in the network.

In this section, a new multi-OLT PON structure for the OAN is proposed to make all the access terminals or ONUs of the PON-based OAN are available to every service provider. In this M-OAN, every ONU will be shared by all the service providers and each OLT will be performed as a CO of a particular service provider.

6.3.1 Network Architecture of an M-OAN

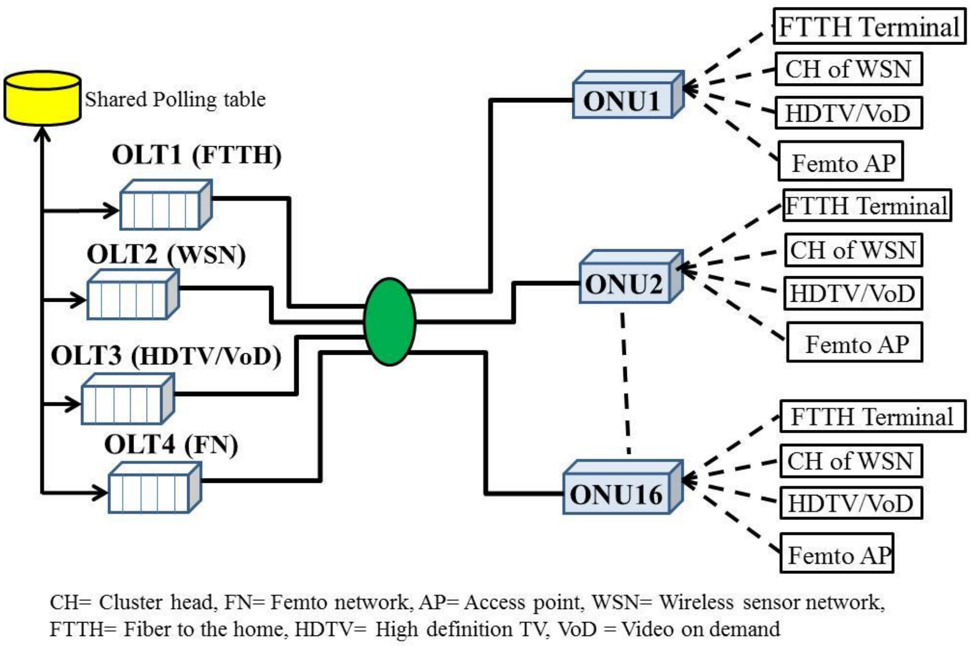


Fig.6.3 Architecture of a multi-OLT PON-based OAN.

A system model for an M-OAN is shown in Fig. 6.3. For convenience, only four OLTs for four service providers have been considered in this figure. Here, the OLT1 is for the FTTH network, the OLT2 is for the WSNs, the OLT3 is for the HDTV/VoD, and the OLT4 is for the FNs. On the other hand, 16 ONUs and each of the ONU is shared by all the four service providers are shown in the figure to represent the proposed M-OAN system model. However, the number of OLTs can be increased depending on the number of service providers in the OAN. Here, all the OLTs contain a common polling table to provide synchronization in both the upstream and downstream transmission channels of the TDM PON. As well as the definition of the OAN it is clear that in the OAN all the access terminals are open to any service provider. That is why, all the four service providers, FTTH, WSNs, HDTV/VoD, and FNs, in an OAN can be connected to each of the ONUs.

In the upstream direction of the M-OAN, data packets from all the ONUs will be received by all the OLTs but every OLT accepts the data packets from a designated service provider. In contrast, in the downstream direction of the M-OAN, all the ONUs accept the broadcasted data packets from every OLT.

6.3.2 Upstream Frame Format of an M-OAN for the Modified LS Scheme

To improve the bandwidth sharing efficiency in a PON system several bandwidth sharing algorithms have been proposed. However, this thesis analyzes the performance of an M-OAN using the modified version of the existing LS scheme. The main objective of this analysis using the LS scheme is just to show that the performances of the proposed network architecture of the OAN are better than those of the S-OAN. The proposed ALDBAM scheme with some modification can be a more suitable algorithm for the M-OAN because the ALDBAM scheme utilizes the multi-OLT PON effect that can be matched with the M-OAN. But, at this stage, this thesis only emphasizes on the modified version of the LS scheme. Figure 6.4 shows the bandwidth sharing principle among the ONUs in the upstream direction for the proposed M-OAN using the modified version of the existing LS DBA algorithm [17]. Here, the maximum transmission window Ω^{max} in the LS scheme is divided by four service providers and the four maximum transmission windows, Ω^{max_1}, Ω^{max_2}, Ω^{max_3}, and Ω^{max_4}, of the four service providers reflect their maximum packet lengths. The number of service providers connected to an ONU is not fixed, as shown the Fig. 6.4 the four service providers are connected to the ONU1 while three service providers are connected to the ONU *N*.

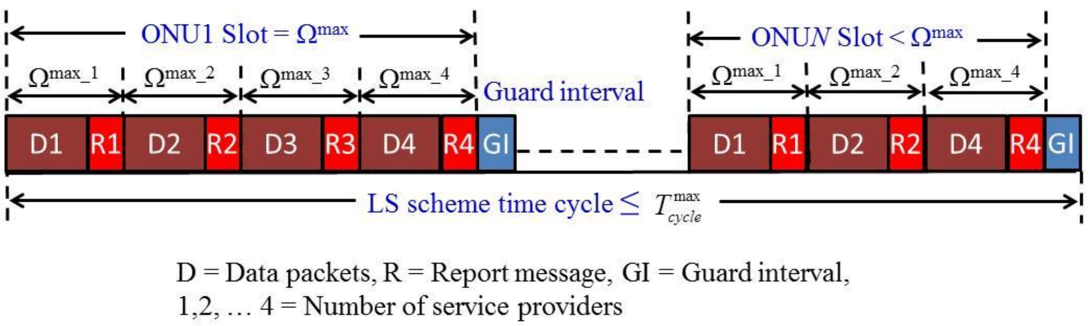


Fig. 6.4 Upstream frame format of an M-OAN for the modified LS scheme.

In a DBA scheme, the length of a time cycle is flexible and maintains an upper bound, i.e., $T_{cycle} \leq T_{cycle}^{max}$. The maximum transmission window for each ONU is $\Omega^{max} = T_{cycle}^{max} / N$, here, *N* is the number of ONUs. In the M-OAN, the Ω^{max} of an ONU has been divided into all the service providers connected to that ONU. Length of the maximum transmission window for each service provider depends on their packet lengths and the number of service providers connected to that ONU. For the upstream transmission in the proposed scheme, four service providers are divided into two groups depending on the generated packet lengths of each service provider. This scheme assumes that the FTTH terminals and the FN are in one group while the WSN and the HDTV/VoD are in another group. The Ω^{max} for each service provider is calculated as follows:

$$\Omega^{max\_1} = \Omega^{max\_4} \text{ and } \Omega^{max\_2} = \Omega^{max\_3} \tag{6.1}$$

$$\Omega^{max} = \Omega^{max\_1} + \Omega^{max\_4} + \Omega^{max\_2} + \Omega^{max\_3} \tag{6.2}$$

here, Ω^{max_1} is the maximum transmission window for the FTTH terminals, Ω^{max_2} is the maximum transmission window for the WSNs, Ω^{max_3} is the maximum transmission window for the HDTV/VoD, and Ω^{max_4} is the maximum transmission window for the FNs.

6.3.3 Timing Diagram of an M-OAN

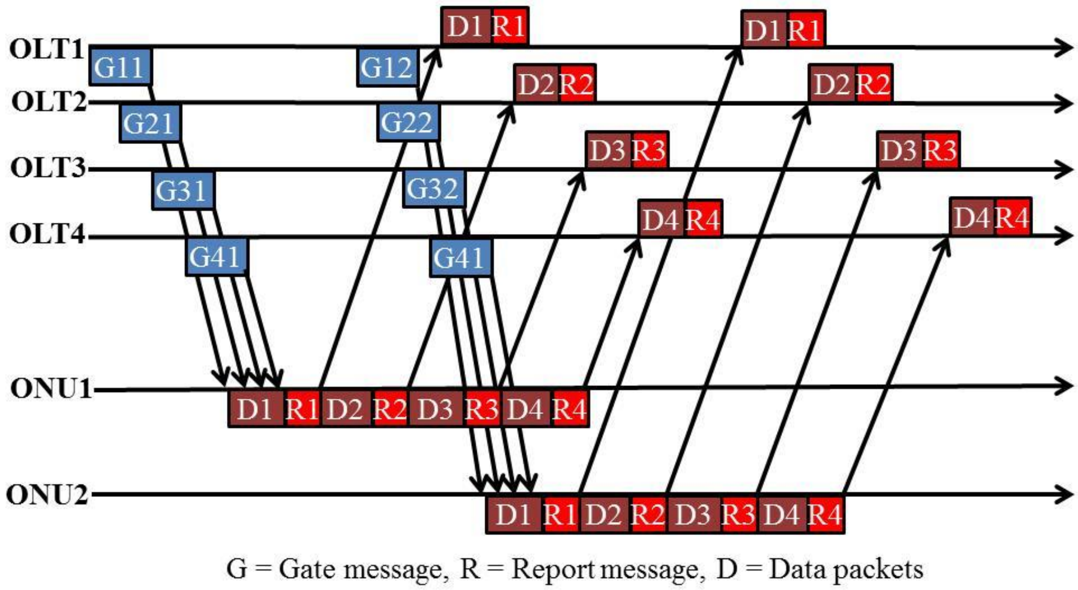


Fig. 6.5 Timing diagram of an M-OAN.

Figure 6.5 shows the timing diagram to schedule the data transmissions among the ONUs and OLTs of an M-OAN. A modified version of the interleaved polling algorithm IPACT is used to avoid collisions and data overlapping. Here, all the OLTs sequentially transmit the Gate messages to every ONU, and an OLT receives the corresponding Report message of a service provider from every ONU.

In the figure, four OLTs transmits the four Gate messages G11, G21, G31, and G41 to the ONU1 from the OLT1, OLT2, OLT3, and OLT4, while every ONU transmits the four Report messages and data packets R1 & D1, R2 & D2, R3 & D3, and R4 & D4 to the OLT1, OLT2, OLT3, and OLT4, respectively.

6.4 Multi-OLT and Multi-Wavelength PON-Based OAN (MM-OAN)

With the evolution of the information and communication technology, several numbers of service providers such as FTTH, WSNs, HDTV/VoD, and FNs have been deployed in the modern cities. A PON-based access network also can be an effective solution for the OAN as it can accumulate data packets of the different service providers in a single PON with better QoSs as explained in the previous chapters of this thesis. Moreover, the M-OAN explained in the previous section is an effective approach to comprise several service providers of an OAN in a single PON. However, comprising so many service providers of an OAN in a TDM PON with a single uplink wavelength creates huge data bottleneck in the single upstream channel. To overcome this problem a multi-OLT PON-based OAN with multiple uplink wavelengths can be an effective solution for obtaining optimum QoSs from the network.

This section explains about the proposed MM-OAN architecture. In this MM-OAN, multiple uplink wavelengths are used for multiple service providers in an ONU and each ONU is shared by all the service providers while the single downlink wavelength is used for the multiple OLTs.

6.4.1 Network Architecture of an MM-OAN

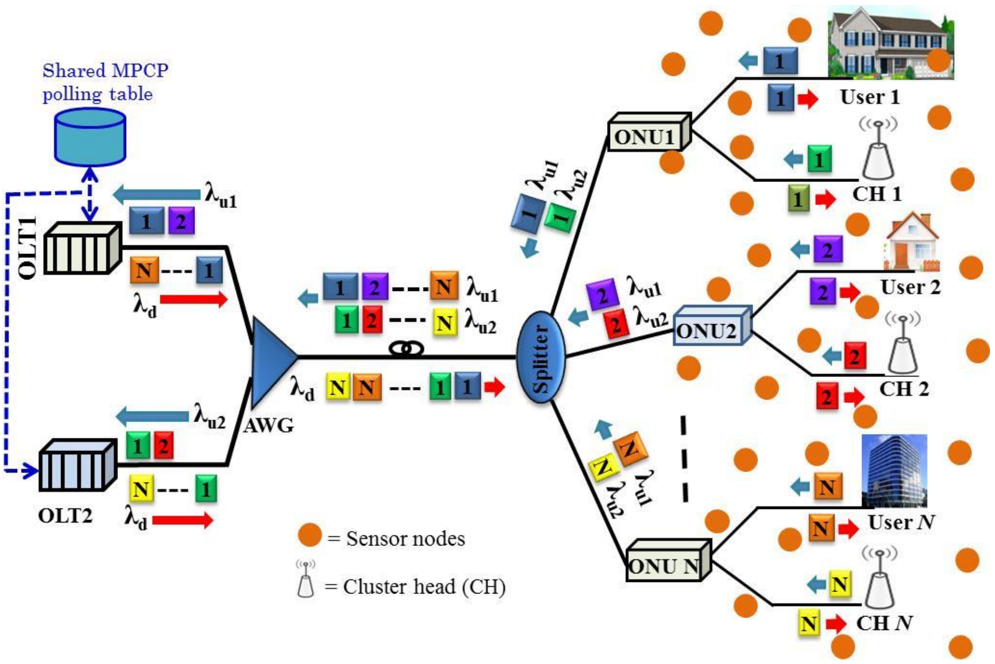


Fig. 6.6 Network architecture of an MM-OAN.

Figure 6.6 shows the proposed MM-OAN concept. Here, only two service providers with two different uplink wavelengths and two different OLTs are shown for simplicity. However, the network can be comprised with *m* service providers where *m* OLTs and *m* upstream wavelengths will be used, but every ONU will be shared by all the service providers.

In the downstream direction of the proposed scheme, each OLT will broadcast data to the network through a passive splitter in a TDMA manner. In the upstream direction of the proposed MM-OAN, the data packets of a particular service provider will be accepted by the designated OLT through a passive splitter and an array waveguide grating (AWG). The upstream channel in a time cycle will be divided by the number of active ONUs N, i.e., $T_{slot}=T_{cycle}/N$. Here, T_{slot} is the time-slot for each ONU in a time cycle. A T_{slot} of an ONU will be occupied by overlapping the data packets from the different service providers by using the different wavelengths.

6.4.2 Upstream Frame Format of an MM-OAN

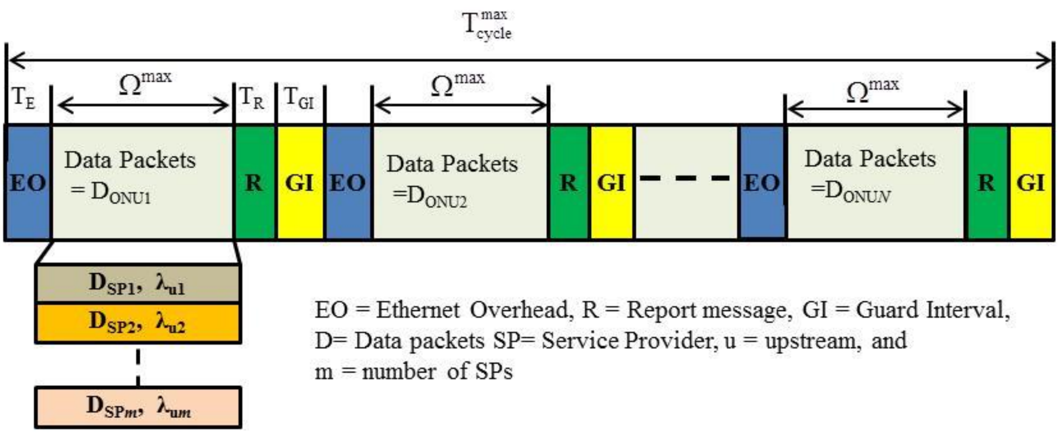
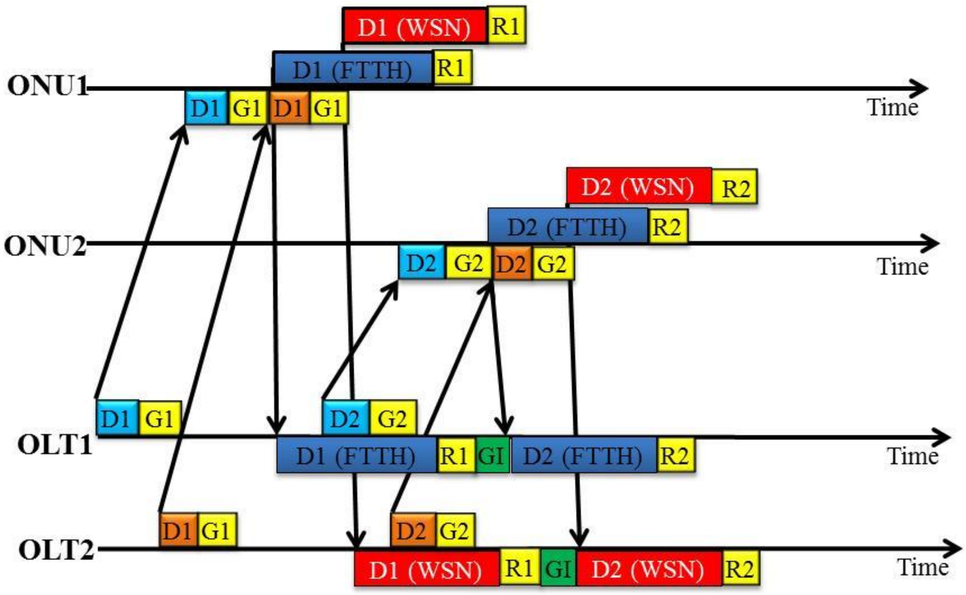


Fig. 6.7 Upstream frame format of an MM-OAN for the modified LS scheme.

Figure 6.7 shows an upstream frame format of an MM-OAN for the modified LS scheme. The MM-OAN also can be analyzed using the modified version of the ALDBAM scheme that would provide better results than the LS scheme. However, this thesis is only limited to the modified version of the LS scheme for performance analysis of the MM-OAN as this scheme is a basic scheme of the PON and any PON architecture can be fairly evaluated by using the LS scheme. The maximum cycle time T_{cycle}^{max} is equally divided into the total number of ONUs N to provide the maximum transmission window Ω^{max} for an ONU, i.e., $\Omega^{max} = T_{cycle}^{max} / N$. Every Ω^{max} is occupied by the data packets from the different service providers using different wavelengths for every service provider. In the figure, the Ω^{max} for the ONU1 is occupied by the data packets D_{SP1}, D_{SP2}, ... and D_{SPm} modulated by the wavelengths λ_{u1}, λ_{u2} , ... and λ_{um} from the service providers 1, 2, … and m, respectively. Here, allocation of the upstream transmission window for every ONU follows the principle of the LS scheme.

6.4.3 Timing Diagram of an MM-OAN



D(WSN)= Data from WSN, D(FTTH)= Data from FTTH terminal, G= Gate message, R= Report message, GI= Guard interval

Fig. 6.8 Timing diagram of an MM-OAN.

Figure 6.8 shows a timing diagram for the proposed MM-OAN. For simplicity, only two service providers connected with every ONU and two OLTs are considered. The scheduling of the control messages follows the modified interleaved polling algorithm for the multi-OLT PON. In the 1st time cycle, all the ONUs receive the downstream data packets and the Gate messages from both the OLTs while, in the 2nd time cycle, all the ONUs transmit the upstream data packets from both the service providers, e.g., WSN and FTTH, by using two different wavelengths. The Upstream packets from every two succeeding ONUs are discriminated by a guard time to avoid the FRTT and data collisions. Even though, two service providers and two OLTs are shown in the figure the number of service providers and the OLTs can be increased up to *m*. In that case, the number of upstream wavelengths also will be *m*. However, the number of the downstream wavelengths is restricted by only one.

6.4.4 Internal Buffer Architectures of an MM-OAN

In order to implement the principle that an ONU is shared by the multiple service providers, modification of the conventional internal buffer architecture in an ONU is required. In the proposed internal buffer structure of the MM-OAN, each ONU consists of multiple buffers for the multiple service providers connected to the ONU. The maximum number of buffers in an ONU depends on the maximum number of service providers connected to that ONU. That means, each buffer of an ONU is devoted for the data packets from a particular service provider.

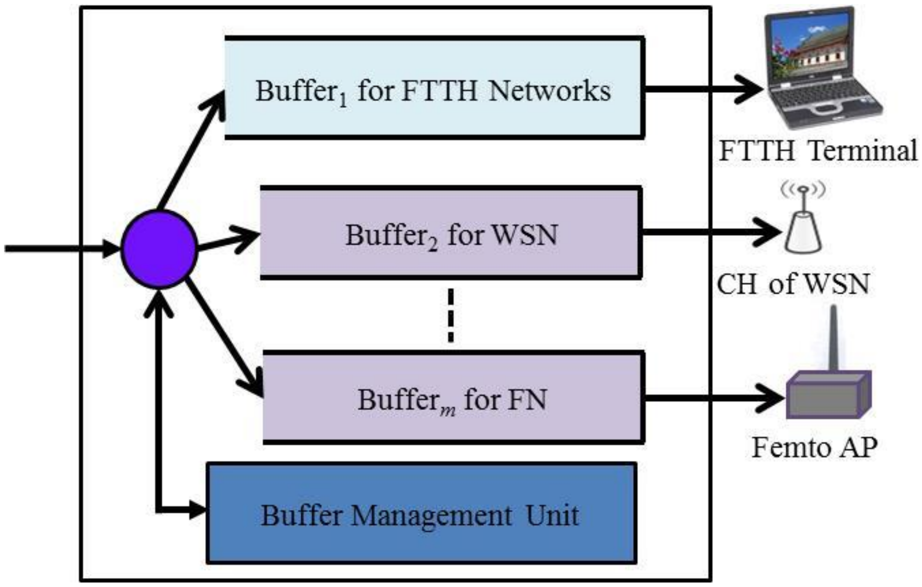


Fig. 6.9 Internal buffer architecture of an ONU for the downstream transmission in an MM-OAN.

The conventional downstream buffer of an ONU is implemented by an external buffer consisting of an off-chip memory and a memory input/outputs (I/Os) [75]. It has a larger capacity with lower cost, but it consumes much more power [76]. In addition, the external buffer must always be in an active mode that is why it cannot reduce the power consumption. Figure 6.9 shows the proposed internal buffer architecture of an ONU for the downstream transmission. In the downstream transmission, each ONU receives data packets from the OLTs and stored in the downstream buffers. After that every ONU transmits data packets from the buffers to the corresponding users connected to that ONU. Here, the internal buffer architecture of an ONU is represented for the *m* different service providers, e.g., the buffer1 for the FTTH networks, the buffer2 for the WSN, … and the buffer *m* for the FN. However, the number of buffers should be directly proportional to the number of service providers connected to an ONU. A buffer management unit (BMU) is also used to monitor and control the downstream data flow to the specific buffer [77].

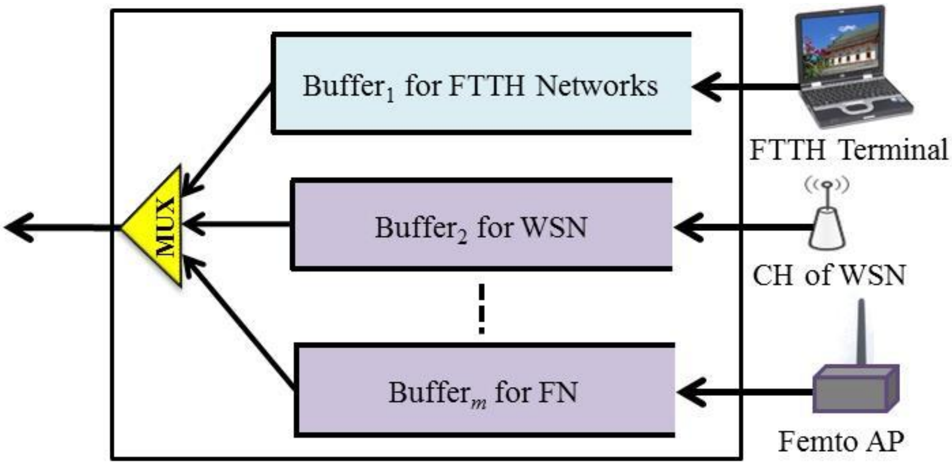


Fig. 6.10 Internal buffer architecture of an ONU for the upstream transmission in an MM-OAN.

Figure 6.10 shows the internal buffer architecture of an ONU for the upstream transmission in an MM-OAN. In the upstream transmission of the MM-OAN, primarily, data are stored in the individual buffer of an ONU from the different service providers, i.e., data from the FTTH terminals are stored in the buffer for the FTTH networks, data from the CH of WSN are stored in the buffer for the WSN, and data from the Femto access points (APs) are stored in the buffer for the FN. Secondly, the stored data from the different buffers are modulated with the different uplink wavelengths and transmitted through an AWG as shown in Fig. 6.10. For the upstream transmission BMU is not required because different uplink wavelengths are used for the different service providers, e.g., wavelengths λ_1, λ_2, … λ_m for the service providers 1, 2, … m, respectively.

6.5 Conclusions

In this chapter, two new network architectures for the PON-based OAN have been presented. All the proposed OAN structures comprise four different service providers in a single optical fiber backbone network with four multiple OLTs. However, the number of service providers and OLTs can be increased up to *m*. These proposed PON-based OAN architectures expressively reduce the installation cost of individual network deployment for every service provider. Moreover, the multiple OLTs also reduce the burden of computational complexity from the data traffics of multiple services in a single OLT and the overall delay. Using the multiple uplink wavelengths in the MM-OAN are very functioning for simultaneous transmissions of the upstream data through a single channel. As explained in the chapter 3, both the M-OAN and MM-OAN also have the same limitation of using a shared polling table.

In both the M-OAN and MM-OAN, true broadband facilities can be provided among all the service providers in a u-City by sharing every ONU by all the service providers in addition to the reduction of installation cost and data processing time. By using the multiple upstream wavelengths for the multiple service providers in the MM-OAN the throughput and bandwidth utilization have been improved by overlapping the single upstream channel for the data packets from the multiple service providers. The main target of this thesis is to provide some hybrid network architectures of the OAN those are effective for comprising several service providers with lower cost and higher QoSs. In this context, the MM-OAN is the best structure for the developing and densely populated countries, e.g., Bangladesh, India, and Pakistan, because by using the multiple upstream wavelengths can make it possible to converge more service providers without compromising any service quality but the installation cost will increase a little amount.

7. Performance Analysis and Simulation Results of the Proposed PON-Based OANs

This chapter presents the performance analysis and simulation results of the proposed M-OAN and MM-OAN. The performances are evaluated in terms of the average packet delay, bandwidth utilization, overhead to data ratio, jitter, upstream efficiency, and throughput by simulation results. In both the M-OAN and MM-OAN, two different OAN architectures with four OLTs for four different service providers, i.e., FTTH, WSN, HDTV/VoD, and FN, and 16 ONUs and each ONU connected to the users of all the service providers were considered in the analysis. Because in an OAN every access terminal is open for all the service providers in the network. A modified version of the LS scheme was used to evaluate the performances of both the M-OAN and MM-OAN. The downstream and upstream channel speeds were considered at 1 Gbps. The distance from an ONU to the OLT is assumed to be random and in the range of 10-20 km. All the data packets were assumed to have the same priority, meaning the service policy was on a FIFO basis with an infinite buffer size for each ONU. Highly bursty self-similar network traffic models were considered for all the service providers. All the four service providers were divided into two groups depending on their maximum packet lengths. The FTTH terminals and FN were in the group one and the maximum packet length for each service provider were considered as1500 bytes while the WSNs and HDTV/VoD were in the group two and the maximum packet length for each service provider was 1024 bytes. The processing time was assumed to be 10 μs for each service provider [52]. All the analyses were performed for a non-uniform offered load in the range of 0-1.0 with a variable cycle time in the range of 0.5-3.0 ms. The simulation took into consideration the queuing delay, transmission delay, congestion delay, and processing delays, without taking into consideration any priority scheduling.

7.1 Performance Analysis of the M-OAN

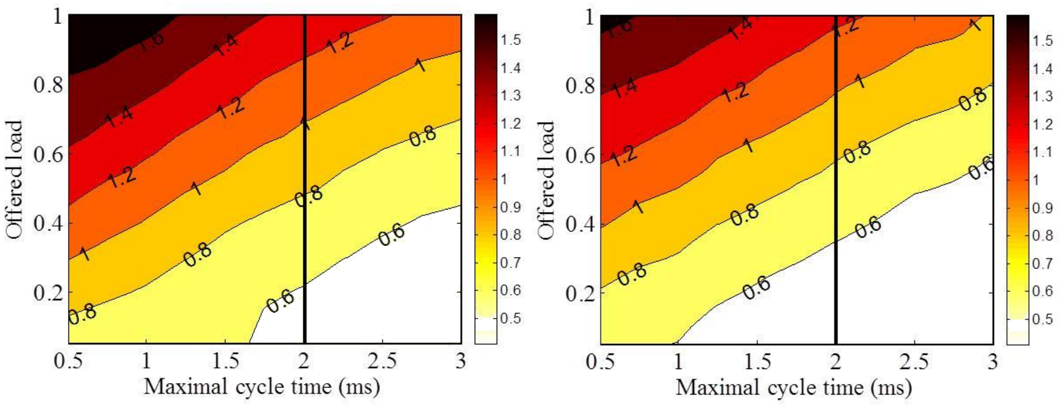
In this section, the performances of the proposed M-OAN are evaluated for the four service providers and 16 ONUs. A single wavelength was considered for both the downstream and upstream transmissions. The simulation parameters are summarized in Table 7.1.

This section also compares the system performance of the proposed M-OAN to that of the single-OLT PON-based OAN (S-OAN). A modified version of the LS scheme was used for the proposed M-OAN while the existing LS scheme was used for the S-OAN.

Table 7.1 Simulation parameters for the M-OAN

Symbol	Quantity	Value
N_{OLT}	Number of OLTs/ service providers	4
N	Number of ONUs	16
D	Distance between OLTs and ONUs	10 to 20km
T_{on}	Laser on time	1.5 µs
T_{off}	Laser off time	1.5 µs
T_{FRTT}	Fluctuation of RTT	1.5 µs
T_{CDR}	Clock and data recovery time	0.5 µs
T_{cycle}	Cycle time	0.5 to 3.0 ms
$B^{max}_{FTTH/FN}$	Maximum packet length for FTTH and FN	1500 bytes
$B^{max}_{WSN/HDTV/VoD}$	Maximum packet length for WSN and HDTV/VoD	1024 bytes
R_U	Transmission speed	1Gbps
T_{proc}	Data processing time for each service provider	10 µs
B_E	Length of Ethernet overhead	576 bits
B_R	Length of Report message	304 bits

7.1.1 Delay



(a) S-OAN (b) M-OAN

Fig. 7.1 Delay in a PON-based OAN.

Figures 7.1(a) and 7.1 (b) show the end-to-end packet delay by using contour plots for the S-OAN and M-OAN, respectively. Both the figures represent the average packet delay using the existing LS scheme for the S-OAN and a modified version of the LS scheme for the M-OAN. From the comparison of these two contour plots it is shown that the M-OAN provides lower packet delay than the S-OAN. The lowest packet delay area in the M-OAN starts from the maximal cycle time of 1.0-ms while the lowest packet delay area in the S-OAN starts from the maximal cycle time of 1.75-ms. That means the M-OAN provides the lowest packet delay even in the lower cycle times than those of the S-OAN. Even though, the same DBA scheme was used to evaluate the end to end packet in both the S-OAN and M-OAN. The main reason for the lower packet delay in the M-OAN is the reduction of data processing time and guard time in the multiple OLTs.

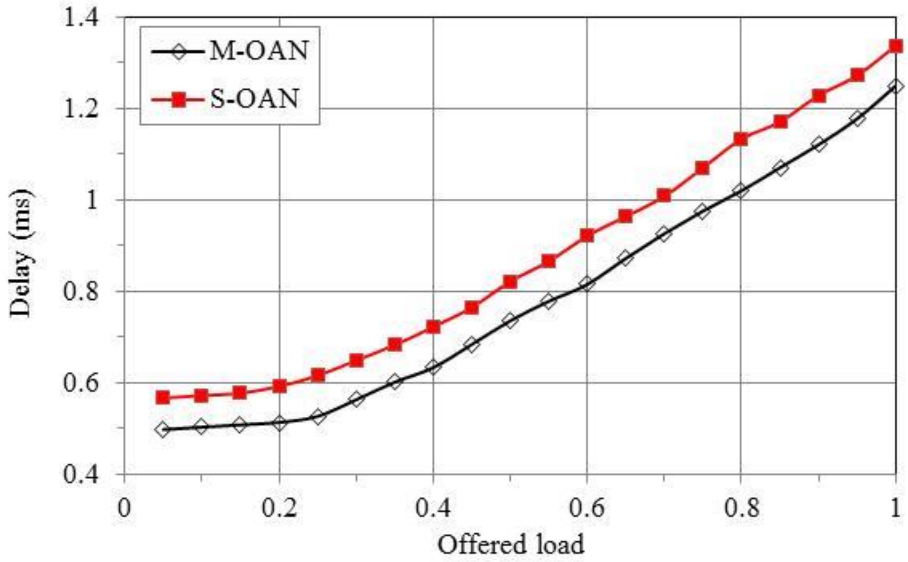
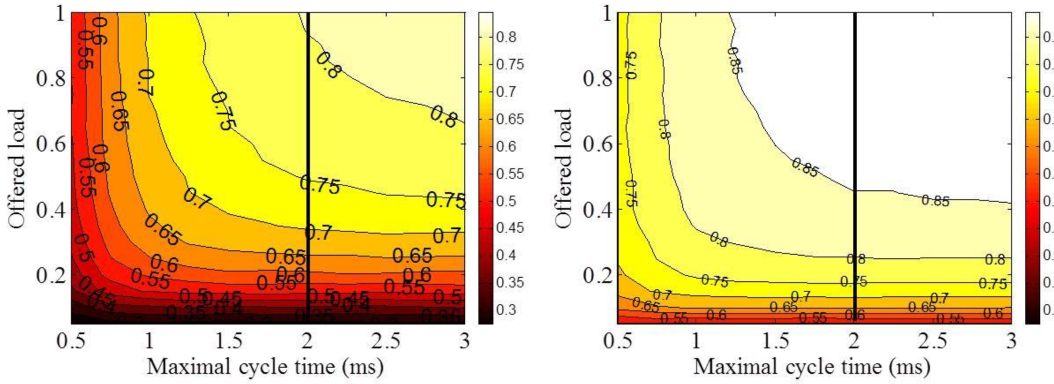


Fig. 7.2 Comparison of average packet delay between the S-OAN and M-OAN for a 2-ms cycle time.

Figure 7.2 shows a comparison of the average packet delay against the offered load between the S-OAN and M-OAN for a 2-ms cycle time. The comparison of the average packet delay for a 2-ms cycle time shows that the proposed M-OAN consistently provides lower packet delay than that of the S-OAN from the lowest offered load of 0.05 to the highest offered load of 1.0. However, the contrast would be more significant if the simulations are repeated for a larger number of service providers and OLTs in the M-OAN.

7.1.2 Bandwidth Utilization

Contour plots in Figs. 7.3 (a) and 7.3 (b) show the bandwidth utilization for the maximal cycle times and offered loads of the S-OAN and M-OAN. The M-OAN provides a wider area of the highest bandwidth utilization of 0.85 in both the directions of cycle time and offered load. However, the S-OAN provides the highest bandwidth utilization of 0.8 and never achieves the bandwidth utilization of 0.85. On the other hand, the lowest bandwidth utilization in the M-OAN is higher than 0.5 while the lowest bandwidth utilization in the S-OAN is less than 0.3.



(a) S-OAN (b) M-OAN

Fig. 7.3 Bandwidth utilization in a PON-based OAN.

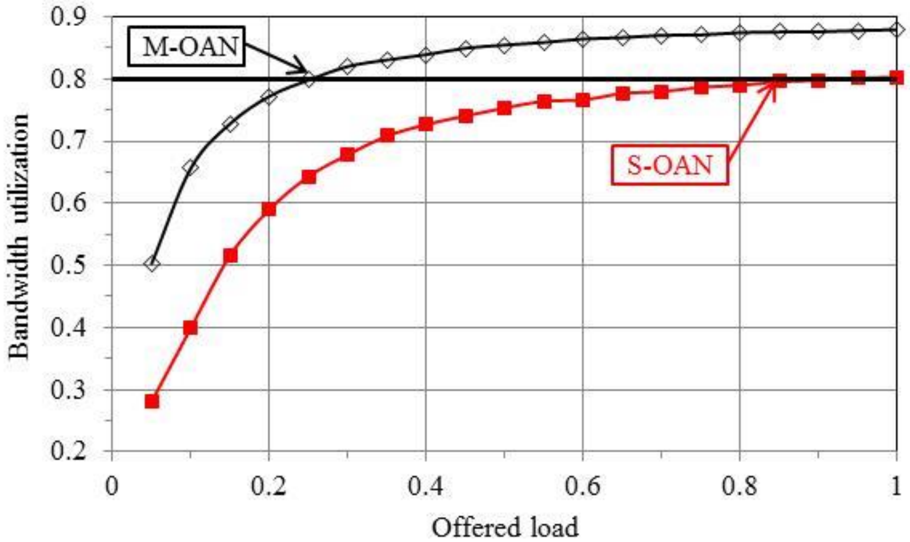
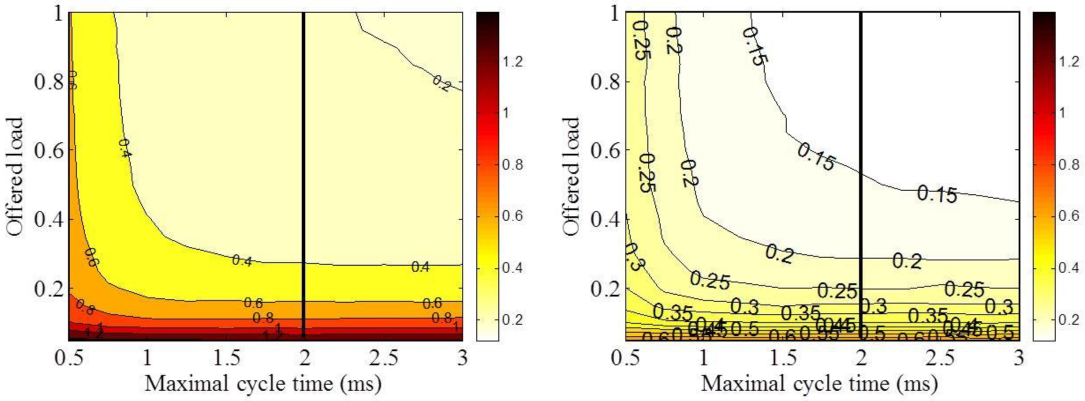


Fig. 7.4 Comparison of bandwidth utilization between the S-OAN and M-OAN for a 2-ms cycle time.

Figure 7.4 provides a comparison of the bandwidth utilization between the S-OAN and M-OAN for a 2-ms cycle time. The M-OAN provides a substantial improvement in the bandwidth utilization than the S-OAN from the lowest offered load of 0.05 and holds the same result until the highest offered load of 1.0. If a horizontal line is drawn at the 80% bandwidth utilization level then it is clear that the M-OAN exceeds the 80% bandwidth utilization level at an offered load of 0.25 while the S-OAN just attains the 80% bandwidth utilization at an offered load of 0.85.

7.1.3 Overhead to Data Ratio



(a) S-OAN (b) M-OAN

Fig. 7.5 Overhead to data ratio in a PON-based OAN.

Overhead to data ratio is an effective parameter that defines the ratio between the wasted bandwidth to the effective bandwidth in the network. It is expected that a network will provide a lower value of the overhead to data ratio. Figures 7.5 (a) and 7.5 (b) provide contour plots of the overhead to data ratio for a range of maximal cycle times and offered loads in the S-OAN and M-OAN. The M-OAN provides a wider area of the lowest overhead to data ratio of 0.15 while the S-OAN never achieve this much lowest overhead to data ratio for any value of the maximal cycle time and offered load. The lowest value of the overhead to data ratio in the S-OAN is 0.2. Moreover, the area of the lowest overhead to data ratio of 0.2 in the S-OAN is very narrow.

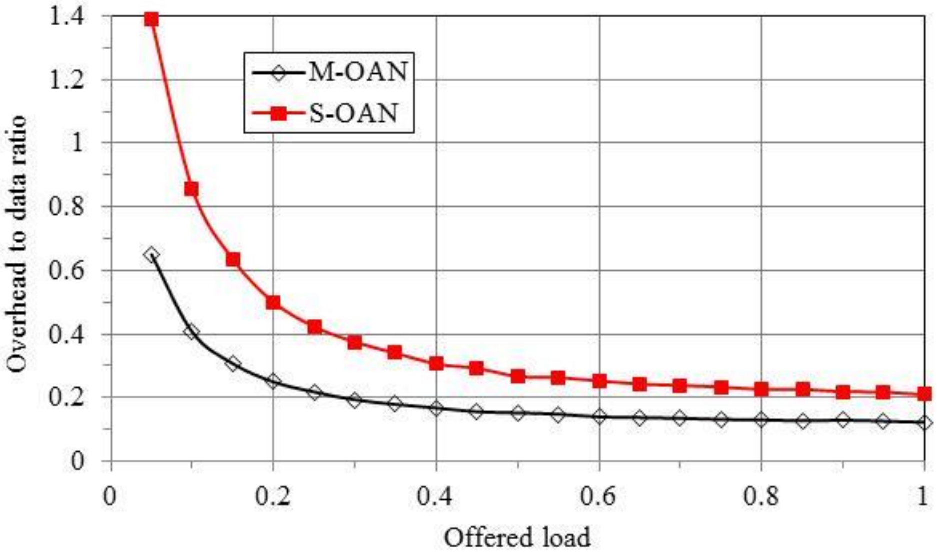


Fig. 7.6 Comparison of overhead to data ratio between the S-OAN and M-OAN for a 2-ms cycle time.

The comparative analysis of the overhead to data ratio between the S-OAN and M-OAN versus a range of offered loads is shown in Fig. 7.6. The M-OAN provides almost 50% less overhead to data ratio than that of the S-OAN from the lowest offered load of 0.05 to the highest offered load of 1.0. Even though the overhead to data ratios are reduced in both the S-OAN and M-OAN in the higher offered loads still the difference is almost 50% between the overhead to data ratios of both the S-OAN and M-OAN.

7.1.4 Upstream Efficiency

Upstream efficiencies in the S-OAN and M-OAN are shown in Figs.7.7(a) and 7.7(b), respectively, by using contour plots for the maximal cycle times and offered loads. The maximum upstream efficiency in the M-OAN is 0.8 and it can be provided from the maximal cycle time of 1-ms to 3-ms with an offered load of 0.075. On the other hand, the maximum upstream efficiency in the S-OAN is 0.7 and it can be achieved from the maximal cycle time of 1.75-ms to 3-ms with an offered load of 2.05. Hence, it can be concluded that the M-OAN can provide better upstream efficiency from a lower value of offered load and cycle time than that of the S-OAN.

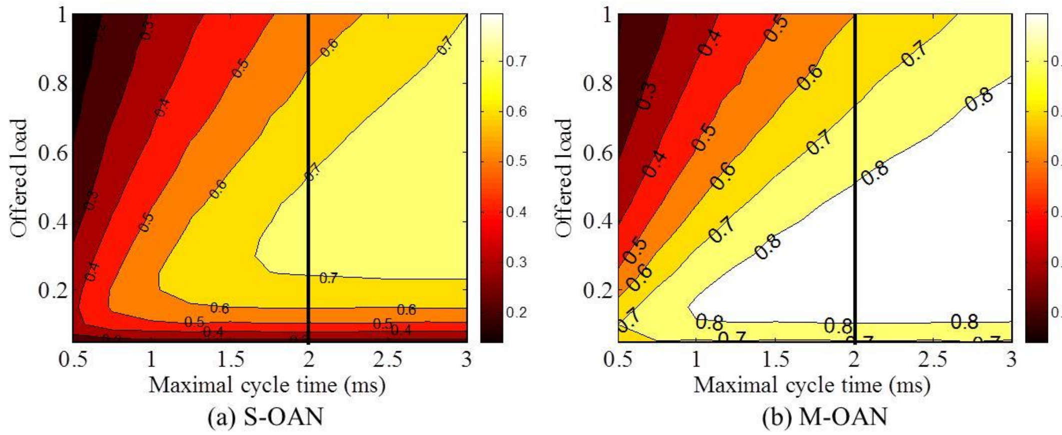


Fig. 7.7 Upstream efficiency in a PON-based OAN.

Comparison of the upstream efficiency between the S-OAN and M-OAN for a 2-ms cycle time is shown in Fig. 7.8. From the comparison of this figure it is shown that the M-OAN provides better upstream efficiency than the S-OAN. However, the M-OAN provides far better upstream efficiency than the S-OAN for the lower offered loads. If a horizontal line is drawn at the 70% upstream efficiency level than it is found that the M-OAN provides about 2.5 times wider offered loads, i.e. from offered loads of 0.05 to 0.75, than the S-OAN, i.e. from offered loads of 0.25 to 0.52.

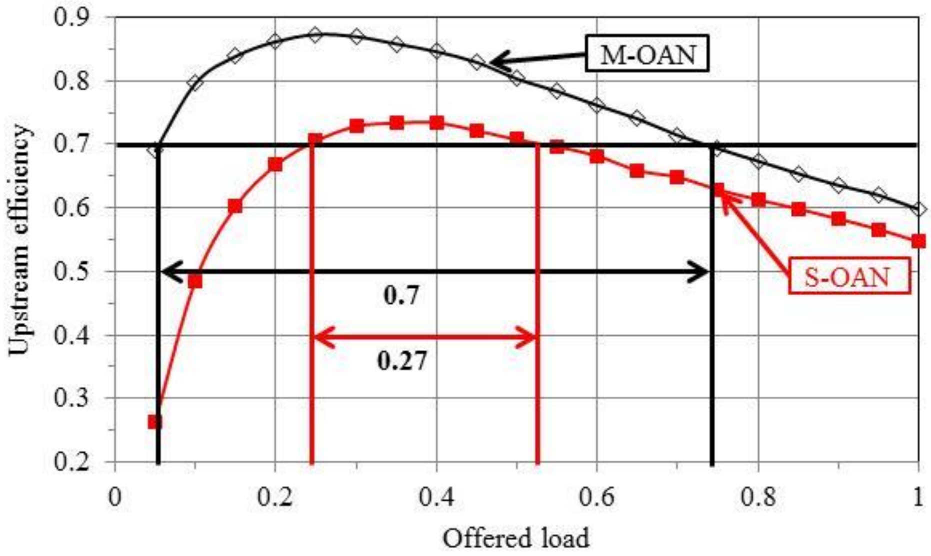


Fig. 7.8 Comparison of upstream efficiency between the S-OAN and M-OAN for a 2-ms cycle time.

7.1.5 Jitter

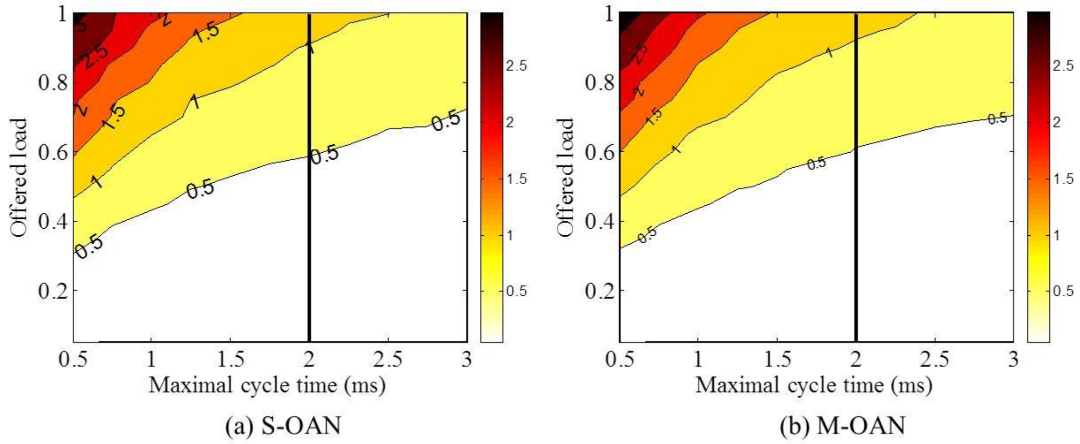


Fig. 7.9 Jitter in a PON-based OAN.

Contour plots of jitter in both the S-OAN and M-OAN are shown in Figs. 7.9(a) and 7.9(b) for different offered loads and cycle times. It is clear that the jitter performance is very similar in both the S-OAN and M-OAN over the range of offered loads of 0.05 to 1 and the range of cycle times of 0.5 to 3-ms. A very close comparison of the jitter between the S-OAN and M-OAN is shown in Fig. 7.10 for a 2-ms cycle time. This figure also reflects the same results as in the contour plots in the Figs. 7.9(a) and 7.9(b). In the M-OAN, a little amount of jitter reduction is achieved for the offered load larger than 0.35. Because the M-OAN reduces the data processing time by using the multiple OLTs and the guard time between every two successive ONUs. It is obvious that the jitter can not be avoided in a

DBA scheme. However, the results in the Figs. 7.9(a), 7.9(b), and 7.10 prove that the proposed M-OAN maintains very close but lower jitter than the S-OAN at the higher offered loads.

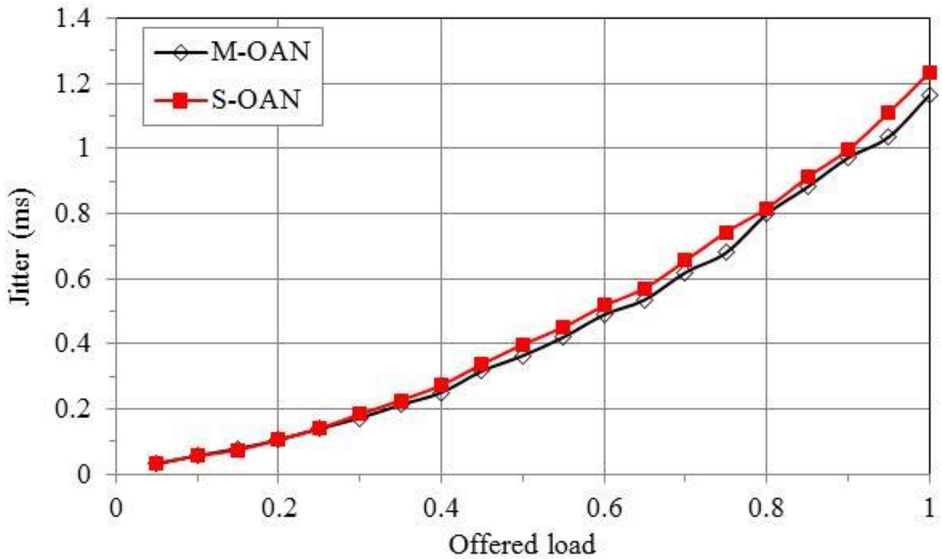


Fig. 7.10 Comparison of jitter between the S-OAN and M-OAN for a 2-ms cycle time.

7.1.6 Throughput

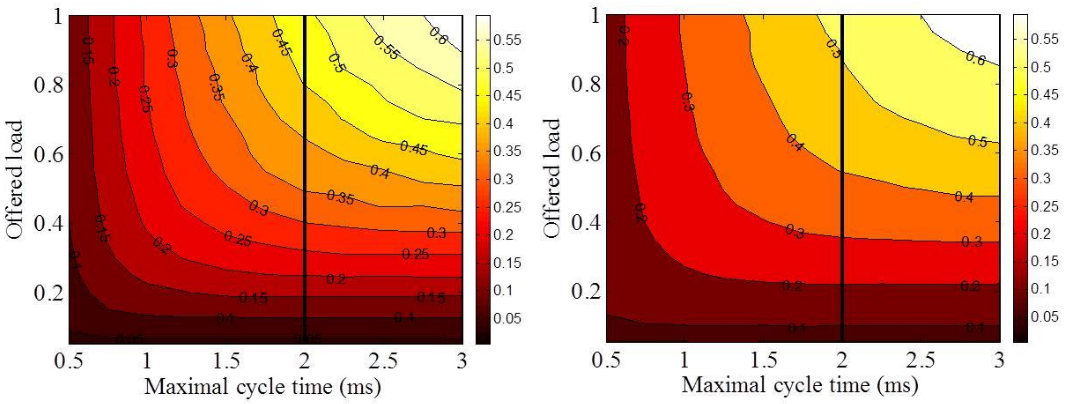


Fig. 7.11 Throughput in a PON-based OAN.

Figs. 7.11(a) and 7.11(b) show throughput for the maximal cycle times and offered loads in the S-OAN and M-OAN. As expected the M-OAN provides a higher throughput than that of the S-OAN alike all other performance parameters explained in the above. Because, the M-OAN deploys multiple OLTs for multiple service providers and provides more effective bandwidth than that of the S-OAN by reducing the data packet processing times for different service providers and guard interval between every two succeeding ONUs.

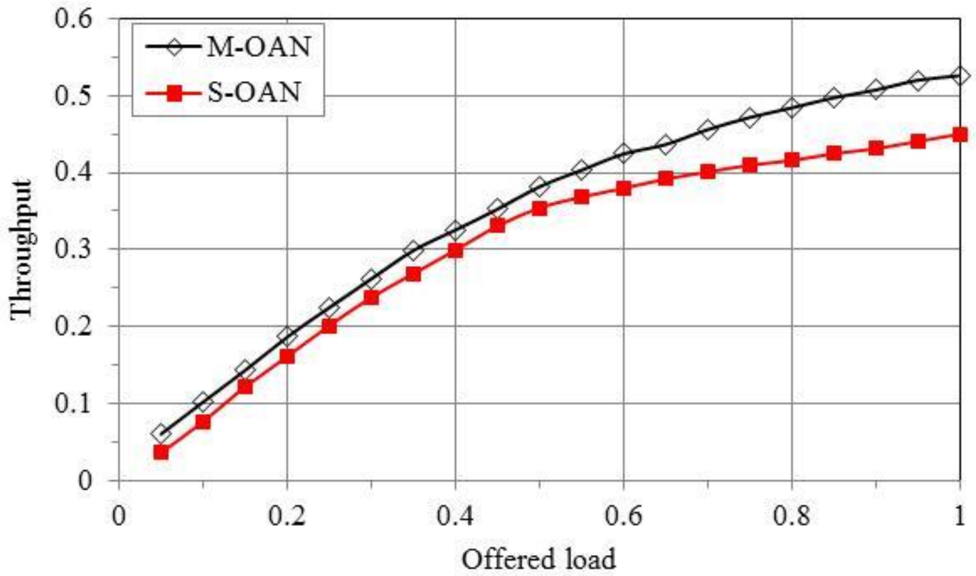


Fig. 7.12 Comparison of throughput between the S-OAN and M-OAN for a 2-ms cycle time.

Figure 7.12 compares the throughput between the S-OAN and M-OAN for a 2-ms cycle time for a range of offered loads of 0.05 to 1.0. As shown in the figure, the M-OAN provides a higher throughput than that of the S-OAN from the lowest offered load of 0.05. However, the difference of the throughput between the M-OAN and S-OAN is increased after the offered load of 0.55 and continues the same tendency up to the highest offered load of 1.0. At the highest offered load of 1.0 the M-OAN providers more than 10% higher throughput than that of the S-OAN.

From the analysis of all the performance parameters in terms of average packet delay, bandwidth utilization, overhead to data ratio, upstream efficiency, jitter, and throughput it is clear that the proposed M-OAN provides better performances than those of the S-OAN in every case. However, the performances of both the schemes were evaluated by using a same DBA scheme, i.e., a modified version of the LS scheme. The main reason of this performance improvement in the proposed M-OAN than the S-OAN is the deployment of multiple OLTs for multiple service providers and this multiple OLTs successfully reduce the computational complexity of data packet processing in a single OLT and the guard intervals in the upstream channel.

7.2 Performance Analysis of the MM-OAN

In this section, the performances of the proposed MM-OAN are evaluated in terms of the bandwidth utilization, overhead to data ratio, jitter, upstream efficiency, and throughput. An OAN architecture with four OLTs for four different service providers, i.e., FTTH, WSN, HDTV/VoD, and FN, and 16 ONUs and each ONU connects with the users of all the service providers were considered in the analysis. A modified version of the LS scheme was also used to evaluate the performances of the MM-OAN. In the upstream direction, four different wavelengths were used while in the downstream direction a single wavelength was considered. In a time cycle, the number of service providers connected to an ONU was assumed to be random and in the range of 1 to 4. That means the number of service providers connected to an ONU was not fixed over the time and this is the real dynamic nature of the network traffics in an OAN. The simulation parameters are summarized in Table 7.2.

Table 7.2 Simulation parameters for MM-OAN

Symbol	Quantity	Value
N_{OLT}	Number of OLTs	4
N	Number of ONUs	16
m	Number of service providers	4
λ_d	Number of downstream wavelengths	1
λ_u	Number of upstream wavelengths	m
T_{proc}	Data processing time per service provider	10μs
T_{cycle}	Cycle time	0.5 to 3.0 ms
T_{GI}	Guard time	5μs
B_E	Length of Ethernet overhead	576 bits
B_R	Length of Report message	304 bits
$B_{FTTH/FN}^{\max}$	Maximum packet length for FTTH and FN	1500 bytes
$B_{WSN/HDTV/VoD}^{\max}$	Maximum packet length for WSN and HDTV/VoD	1024 bytes

This section also compares the performances among the proposed MM-OAN to the S-OAN and M-OAN. Where, a single wavelength was considered for both upstream and downstream transmission in both the S-OAN and M-OAN.

7.2.1 Bandwidth Utilization

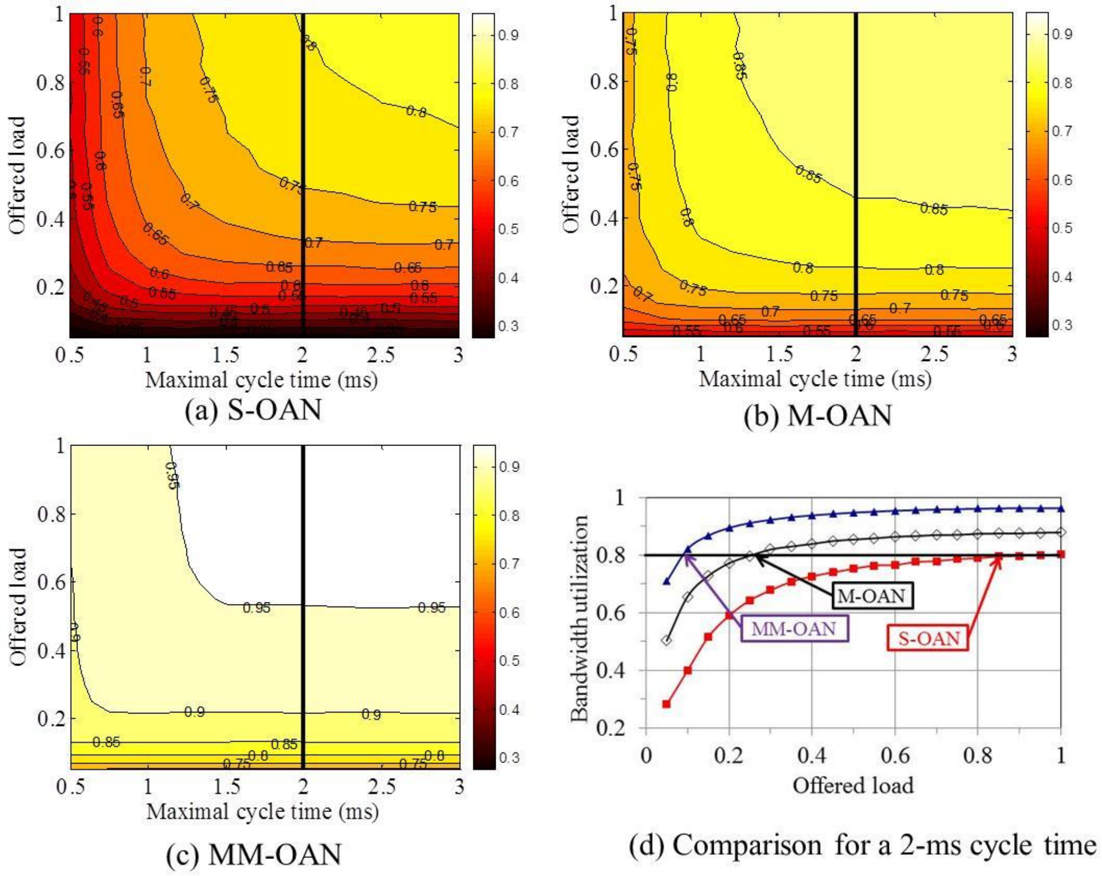


Fig. 7.13 Bandwidth utilization in the S-OAN, M-OAN, and MM-OAN.

Figures 7.13(a), 7.13(b), and 7.13(c) show the bandwidth utilization for the conventional LS scheme in the S-OAN, and a modified version of the LS scheme in the M-OAN and MM-OAN, respectively. These contour plots for the maximal cycle times and offered loads signify the performance of the three proposed architectures in term of the bandwidth utilization. The highest bandwidth utilization area in the MM-OAN is 0.95 while the highest bandwidth utilization area in the M-OAN is 0.85 and in the S-OAN is 0.8.

Figure 7.13(d) shows a close comparison of the bandwidth utilization among the MM-OAN, M-OAN, and S-OAN for a 2-ms cycle time. From this figure it is found that the MM-OAN exceeds the 80% bandwidth utilization line at an offered load of 0.1, and the M-OAN exceeds that at an offered load of 0.25. However, the S-OAN just touches the 80% bandwidth utilization line at an offered load of 0.85. Therefore, the MM-OAN provides higher bandwidth utilization from a very lower offered load than those of the M-OAN and S-OAN for a 2-ms cycle time.

7.2.2 Overhead to Data Ratio

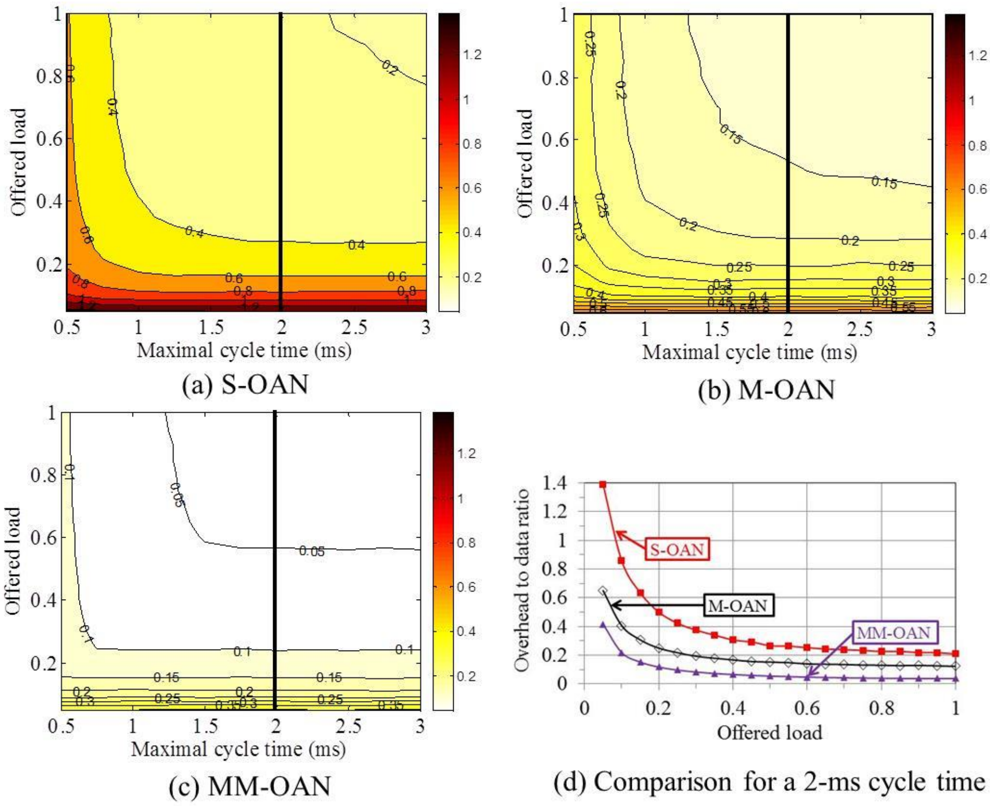


Fig. 7.14 Overhead to data ratio in the S-OAN, M-OAN, and MM-OAN.

Contour plots in Figs. 7.14(a), 7.14(b), and 7.14(c) show overhead to data ratio in the S-OAN, M-OAN, and MM-OAN for wider ranges of maximal cycle times and offered loads. As it is known that lower overhead to data ratio represents better bandwidth utilization and QoSs. From the comparison of these figures it is crystal clear that the MM-OAN provides a far wider area of lower overhead to data ratio in both the directions of offered loads and maximal cycle times than both the M-OAN and S-OAN. The lowest overhead to data ratio in the MM-OAN is 0.05 whereas the lowest overhead to data ratios in the M-OAN and S-OAN are 0.15 and 0.2, correspondingly. The comparison of the overhead to data ratio among the three schemes is shown in Fig. 7.14(d) for a 2-ms cycle time. As shown in the contour plots this figure also shows that the MM-OAN provides the best result for all the offered loads where the MM-OAN provides more than 200% and 450% less overhead to data ratio than the M-OAN and S-OAN at an offered load of 1.0.

7.2.3 Upstream Efficiency

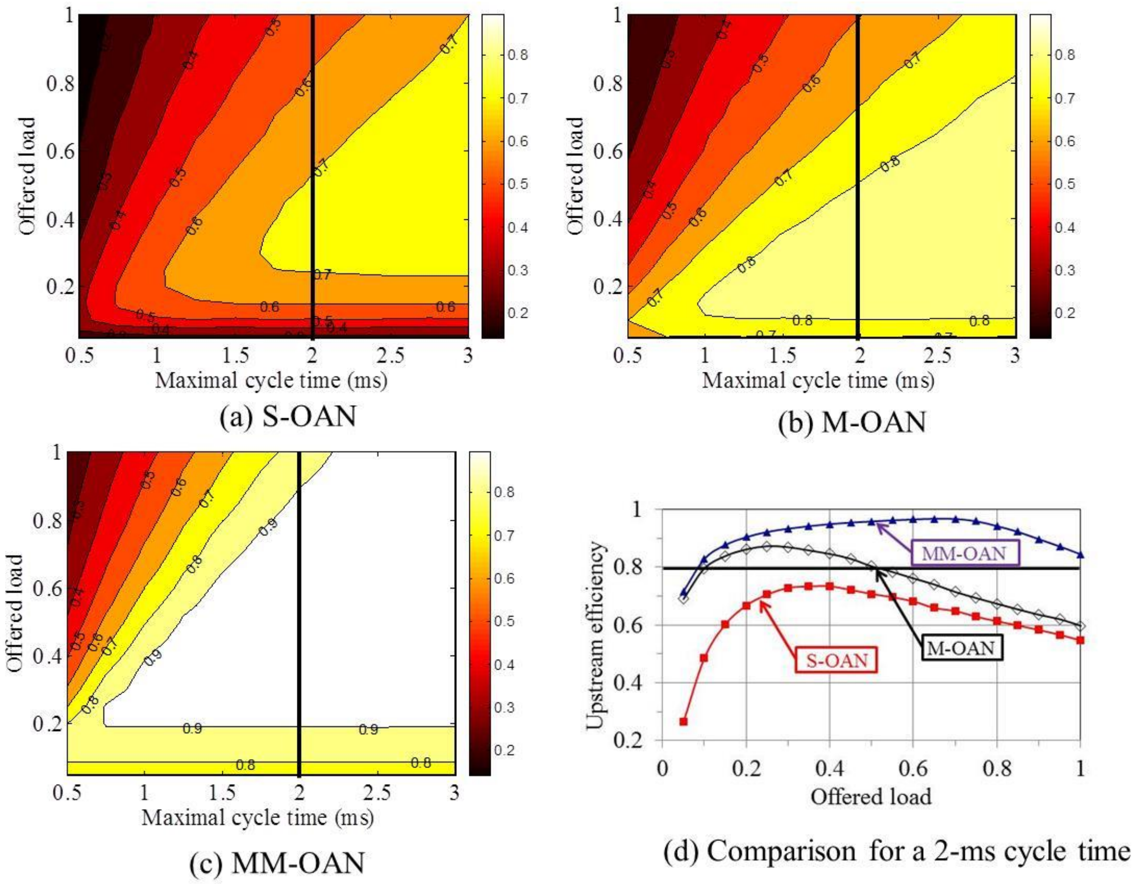


Fig. 7.15 Upstream efficiency in the S-OAN, M-OAN, and MM-OAN.

Figs. 7.15 (a), 7.15(b), and 7.15(c) show the upstream efficiencies of the S-OAN, M-OAN, and MM-OAN by using contour plots. The analysis of the three contour plots shows that the MM-OAN provides a wider area of the highest upstream efficiency of 0.9. In contrast, the M-OAN and S-OAN provide the highest upstream efficiency of 0.8 and 0.7, respectively. Comparison of the upstream efficiencies among the MM-OAN, M-OAN, and S-OAN for a 2-ms cycle time is shown in Fig. 7.15(d). For better analysis a horizontal line is drawn at the 80% upstream efficiency level in the Fig. 7.15(d) and the MM-OAN exceeds the 80% upstream efficiency level before the offered load of 0.1 and the M-OAN exceed the 80% upstream efficiency level at an offered load of 0.1. Moreover, the MM-OAN maintains the upstream efficiency higher than 80% until the highest offered load of 1.0 while the M-OAN can maintain that until the offered load of 0.5. In contrast, the S-OAN never touches the 80% upstream efficiency level. Therefore, it can be concluded that the MM-OAN is the best PON-based OAN architecture in term of the upstream efficiency for any value of the offered load and cycle time.

7.2.4 Jitter

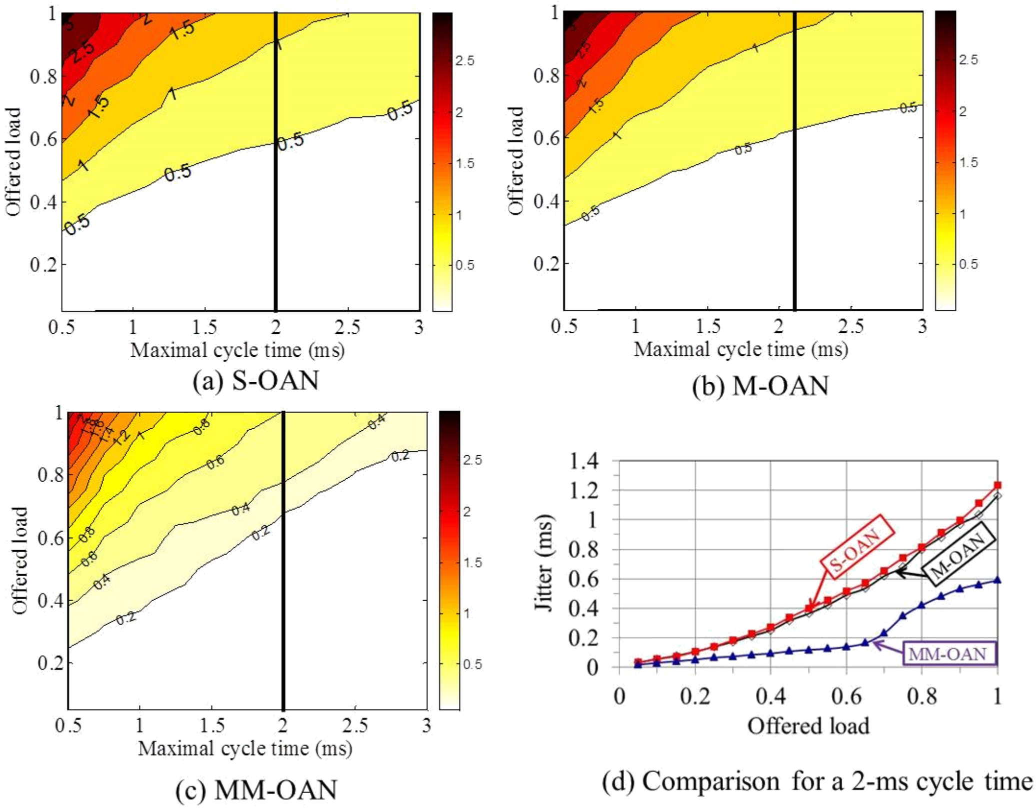


Fig. 7.16 Jitter in the S-OAN, M-OAN, and MM-OAN.

Even though the M-OAN and S-OAN provide similar and very close jitter performances but the MM-OAN provides significantly less jitter than both the M-OAN and S-OAN as shown in Figs. 7.16(a), 7.16(b), and 7.16(c). The MM-OAN provides a wider area of the lowest jitter of 0.2 while both the M-OAN and S-OAN provide wider areas of the lowest jitter of 0.5. Figure 7.16(d) compares the jitter performances for a 2-ms cycle time among the three schemes over a wider range of offered loads. This figure signifies that the MM-OAN is far better in term of the jitter performance from a very lower value of offered load to the highest offered load of 1.0 than that of the M-OAN and S-OAN.

7.2.5 Throughput

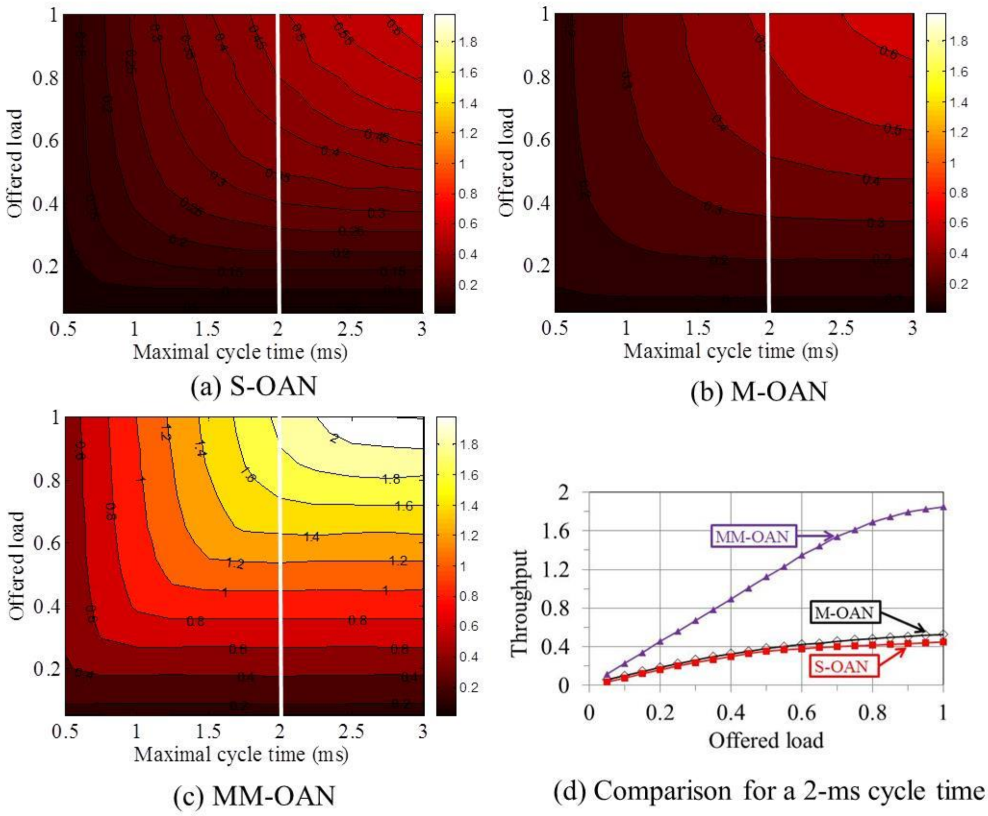


Fig. 7.17 Throughput in the S-OAN, M-OAN, and MM-OAN.

Figures 7.17(a), 7.17(b), and 7.17(c) provide an analysis of throughputs for the S-OAN, M-OAN, and MM-OAN, respectively. In these contour plots the MM-OAN provides the maximum throughput of 2 Gbps while the maximum throughput in both the M-OAN and S-OAN is 0.6 Gbps. Here, the MM-OAN provides the maximum throughput that is higher than the bandwidth of the network of 1 Gbps. The main reason of this higher throughput is that the MM-OAN uses the simultaneous transmissions of multiple upstream packets by using the multiple wavelengths for the multiple service providers connected to an ONU. Figure 7.17(d) compares the throughput vs offered load among the S-OAN, M-OAN, and MM-OAN for a 2-ms cycle time. The MM-OAN provides more than 350% higher throughput than the M-OAN and more than 400% higher throughput than the S-OAN at an offered load of 1.0.

From the analysis of all the performance parameters in terms of bandwidth utilization, overhead to data ratio, upstream efficiency, jitter, and throughput it can be concluded that the proposed MM-OAN provides better performances than those of both the M-OAN and S-OAN in every case. The main reason of this performance improvement in the proposed MM-OAN than both the M-OAN and S-OAN is the use of the multiple upstream wavelengths and simultaneous transmissions in the upstream channel by the multiple service providers.

7.3 Comparisons Among the S-OAN, M-OAN, and MM-OAN

This section compares the performances of the proposed two architectures of the PON-based OAN, M-OAN and MM-OAN, to those of the architecture of the S-OAN. All the performances for both the proposed M-OAN and MM-OAN were analyzed for a modified version of the LS scheme while the conventional LS scheme was used for the S-OAN. Here, only a little modification was done in the LS scheme to make it suitable for the proposed multi-OLT structures. Actually, the LS scheme is a very basic DBA algorithm for the PON system and it is fair to compare the performances of any PON architecture using this DBA scheme. The main objective of these proposed OAN structures is to provide better QoSs whereas several service providers in a u-City will be comprised with their own features and the multiple OLTs will share the processing complexities of data packets of the multiple service providers and provided that overall network installation cost will be reduced. To prove that the proposed schemes are better than the S-OAN this thesis elaborately compares the performances of the proposed M-OAN and MM-OAN with those of the S-OAN using the same DBA scheme, i.e., LS scheme, in terms of bandwidth utilization, overhead to data ratio, upstream efficiency, and throughput in the previous sections of this chapter by using simulation results. From the comparative analysis of the simulation results, explained in the above sections of this chapter, it is clear that as expected the M-OAN provides better performances than the S-OAN whereas the MM-OAN is the best structure. However, the MM-OAN requires higher installation cost than both the M-OAN and S-OAN because it uses multiple upstream wavelengths. Moreover, both the M-OAN and MM-OAN have the complexity of sharing a single polling table that restricts the installation of the multiple OLTs in different buildings.

Table 7.3 shows brief comparisons among the S-OAN, M-OAN, and MM-OAN architectures. All the numerical values in the Table 7.3 represent for a 2-ms cycle time, 16 ONUs and each ONU is connected to maximum four service providers, maximum offered load of 1.0, and data policy for all the schemes were FIFO basis. The S-OAN structure was evaluated by using the LS scheme whereas both the M-OAN and MM-OAN structures were evaluated by using the modified version of the LS scheme. Here, the S-OAN and M-OAN schemes were used for a single upstream wavelength while the MM-OAN was used for 4 upstream wavelengths. Both the M-OAN and MM-OAN were considered for deployment of 4 OLTs while a single OLT was considered for the S-OAN. The number of service providers connected to an ONU at a time cycle was considered as random in the range of 1 to 4.

Table 7.3 Comparisons among the S-OAN, M-OAN, and MM-OAN

Quantity	S-OAN	M-OAN	MM-OAN
Number of OLTs	One	Four	Four
Number of service providers, *m*	Four	Four	Four
Shared polling table	No	Yes	Yes
Cost	Low	Medium	High
Complexity	Low	Medium	Medium
Bandwidth utilization	0.80	0.88	0.96
Overhead to data ratio	0.21	0.12	0.04
Upstream efficiency	0.55	0.60	0.84
Jitter in ms	1.23	1.16	0.59
Throughput in Gbps	0.45	0.53	1.85

7.4 Conclusions

In this chapter, performances of the proposed two different network architectures of the PON-based OAN, i.e., M-OAN and MM-OAN, using the modified version of the LS scheme have been numerically analyzed in terms of average packet delay, bandwidth utilization, overhead to data ratio, upstream efficiency, jitter, and throughput. All the analyses were done for a range of non-uniform traffic loads and cycle times. The proposed M-OAN and MM-OAN commendably utilize and share the huge bandwidth of the optical network for the multiple service providers in a u-City and reduces the computational complexity of data packet processing.

The proposed M-OAN structure is a true broadband concept that provides convergence of the multiple service providers in a u-City. From the analysis of several performance parameters and comparison with those of the S-OAN using the LS scheme, it is clear that the M-OAN provides better results in every analysis for both the low and high traffic loads.

Finally, the performances of the proposed MM-OAN are compared to both the M-OAN and S-OAN. The MM-OAN provides tremendous improvements in several performance parameters than both the M-OAN and S-OAN because it effectively utilizes both the multi-OLT and multi-wavelength effect on the upstream channel. Specially, throughput in the MM-OAN is almost 400% and 350% higher than that of the S-OAN and M-OAN, respectively, for four service providers and offered load of 1.0 at a 2-ms cycle time. However, this difference will be increased proportionally with the number of service providers in the network.

The performances of both the M-OAN and MM-OAN would be more improved if all the analysis were done for the modified version of the ALDBAM scheme. But, in this thesis, the research on the M-OAN and MM-OAN have been just in the beginning stage and for better and fair comparisons all the S-OAN, M-OAN, and MM-OAN structures were analyzed for the LS scheme.

8. Conclusions

The FTTH access network has been considered as the highly valued and most popular choice for the present age broadband access networks. However, with the increasing and dynamic popularity of the internet consisting of high speed, real time application, and high quality services the bandwidth demand is one of the prime requirements. Moreover, several new service providers, e.g., WSN, HDTV/VoD, and FNs, are also going to be more popular in the modern u-Cities. The convergence of these service providers in a single access network is the main challenge in the future technological development. A PON-based hybrid network is a highly favored scheme for comprising those services with great advantages such as: Low price, flexible protocol, sufficient bandwidth, and matured technology. The scope of this thesis is focused on designing several new network structures of the hybrid PON comprising multiple service providers and providing appropriate DBA algorithms compatible for those new network architectures, as this PON-based access technology has many advantages over the other possible alternatives.

This thesis mainly emphasizes on several innovation points of the PON-based hybrid networks and all the proposals can be divided into two groups: (1) Network architectures, i.e., single-OLT PON-based hybrid FTTH and WSNs, multi-OLT PON-based hybrid FTTH and WSNs, M-OAN, and MM-OAN, (2) DBA algorithms, i.e., ALDBA1 and ALDBA2 schemes for the single-OLT PON-based hybrid networks, and ALDBAM scheme for the multi-OLT PON-based hybrid networks.

In the single-OLT PON-based hybrid networks, two different service providers, i.e., FTTH and WSNs, are effectively combined in a single PON and shares a single optical channel. Here, the data packets of the two different service providers consist of different packet lengths and data rates. This structure effectively reduces the enormous expense and time for deployment of separate backbone networks for each service provider. Because, constructing a closed, and specific-use network infrastructure for each individual application and accommodating several users using different access terminals and servers require an enormous amount of time and expense.

In the multi-OLT PON-based hybrid networks, multiple service providers share a single optical network. Deployment of the multiple OLTs for the multiple service providers in a single PON makes it possible to independently handle the data packets of an operator by an OLT. Because all of these service providers have several features, e.g., device capacity diversity, application diversity, mobility, numbering and routing diversity, security, and privacy, and these features provide additional encumbrance of processing on a single OLT. That is why, the multi-OLT PON structure effectively reduces the computational complexity of data packet processing and guard interval between every two sequential ONUs by using proper guard time management.

In the MM-OAN, every ONU is shared by all the service providers and every service provider communicates with a designated OLT by using an individual uplink wavelength for each service provider. In this scheme, the upstream data packets from the multiple service providers are simultaneously transmitted through a single optical channel by using multiple uplink wavelengths. As a result significant improvements are achieved in terms of throughput and bandwidth utilization. This scheme can be very much effective in the developing and over populated countries, e.g., Bangladesh, India, and Pakistan, where new PON-based network infrastructure is going to be deployed. In these countries, the most challenging factor to deploy a new network is its expense as most of the people are poor and their income level is very low. However, providing them a technologically rich environment is the most prime requirement to make them developed. This scheme significantly reduces the network deployment cost that will be very helpful for the users to reduce their expenses.

The performances of all the above network architectures have been conducted through simulations using several new DBA algorithms and a modified version of the existing LS scheme. The main results of this thesis include the following:

For the single-OLT PON-based hybrid networks of the FTTH and WSNs, two new DBA algorithms, the ALDBA1 and ALDBA2 schemes, have been presented. For the first time in the history of PON, two different maximum transmission windows have been considered for the two different service providers for improving the bandwidth sharing efficiency among the two service providers in the network. The ALDBA1 scheme is a simpler algorithm than the ALDBA2 scheme that provides a significant improvement in every performance parameter than the conventional LS scheme. In contrast, the ALDBA2 scheme is more complicated because it requires more mathematical operations than both the LS and ALDBA1 schemes. However, the ALDBA2 scheme is the best scheme for the single-OLT PON-based hybrid networks in terms of delay, bandwidth utilization, upstream efficiency, jitter, and throughput for a wider range of both the cycle time and offered load. The proposed schemes provide better QoSs than the LS scheme for the delay sensitive services. From the quantitative comparisons of several performance parameters between the ALDBA2 and LS schemes it is found that the ALDBA2 scheme provides 60% lower delay with 33% higher upstream efficiency and 30% higher throughput than those of the LS scheme for the offered load of 1.0 and a 2-ms cycle time.

For the multi-OLT PON-based hybrid networks of the FTTH and WSNs, a new DBA algorithm, the ALDBAM scheme, has been presented. The ALDBAM scheme is an unparalleled DBA algorithm that considers multiple OLTs in the CO to reduce the computational complexity of data packet processing and employ with the proper guard time management to reduce the total guard interval.

This scheme is specially designed for the multi-OLT PON and there is no existing DBA algorithm designed for a multi-OLT PON. However, this thesis presented a comparative analysis of the performance of the ALDBAM scheme with that of the ALDBA1 and ALDBA2 schemes for the single-OLT PON-based hybrid networks. The ALDBAM scheme copes with all the limitations of the ALDBA1 and ALDBA2 schemes and the simulation results signify that the ALDBAM scheme provides better bandwidth sharing efficiency and utilization than both the ALDBA1 and ALDBA2 schemes even for a smaller cycle time and lower offered load. When the performances of the ALDBAM scheme are compared to those of the existing LS scheme for the single-OLT PON then the ALDBAM scheme provides 115% less delay with 45% higher upstream efficiency and 40% higher throughput than those of the LS scheme at the offered load of 1.0 and 2-ms cycle time. Moreover, the effectiveness of the ALDBAM scheme will be more significant for a larger number of OLTs and service providers as expected to be deployed in the developing and over populated countries.

In the M-OAN, multiple OLTs are deployed in the CO of the OAN to reduce the data processing time. Even though, the performance of the M-OAN will be more significant for a larger number of service providers connected the ONUs in an OAN still the performance of the M-OAN is better than the conventional S-OAN for the four service providers connected to every ONU.

In the MM-OAN, multiple upstream wavelengths are used for the multiple service providers in addition to the multiple OLTs in the M-OAN. This scheme is very much effective for reducing the overhead to data ratio and improving the throughput than both the S-OAN and M-OAN. The MM-OAN uses the multiple uplink wavelengths for the multiple service providers for this reason it will require a little bit higher installation cost than the M-OAN. However, the MM-OAN provides a very significant performance improvement in terms of the bandwidth utilization, upstream efficiency, overhead to data ratio, jitter, and throughput than those of the M-OAN. As shown in the comparison Table 7.3 in the chapter 7 it can be mentioned that the MM-OAN provides 400% and 350% higher throughput with 50% and 45% lower jitter than those of the S-OAN and M-OAN, respectively, at the offered load of 1.0 and 2-ms cycle time. That is why the MM-OAN will be a very effective scheme for the huge users' areas of the densely populated countries, e.g., Bangladesh, India, and Pakistan, where a larger number of service providers will be installed.

In this dissertation several variations of a totally new network concept of a hybrid PON and OAN have been proposed those are: multi-OLT PON-based hybrid FTTH and WSNs, M-OAN, and MM-OAN. Those network structures require a shared polling table for the multiple OLTs to maintain synchronization in the upstream transmissions. However, in the practical scenario for sharing a single polling table is that the multiple OLTs should be installed in the same place that will defect the beauty of the technological flexibilities in the PON even though all these structures have provided a great improvement in all the performance parameters. That is why, the future challenge of this research is to find out the way how to overcome this problem that will make it possible to provide synchronization without sharing a single polling table or a single polling table can be shared by the multiple OLTs from apart. Moreover, in the MM-OAN a single downstream wavelength is used for multiple service providers but with the increasing demands of the huge populated areas the multiple wavelengths can be introduced in the downstream direction in the future research.

All the novel DBA algorithms proposed in this thesis provide higher bandwidth sharing efficiency and fairness as well as bandwidth utilization. All the simulation results and comparisons to the existing DBA scheme prove the contribution and validity of these DBA schemes. However, in this thesis, all the analyses have been presented only for the upstream traffics and still there is a chance to implement these proposed schemes for the downstream direction. In the future works, the proposed DBA schemes will enhance for analyses of several performances of the downstream packets in the multi-OLT PON-based hybrid networks. Because in a multi-OLT PON, a single downstream channel is shared by the multiple OLTs that requires a bandwidth allocation scheme for improving bandwidth sharing efficiency among the multiple service providers in the downstream channel.

This thesis has not considered about any new DBA algorithms for the proposed M-OAN and MM-OAN. In this thesis, the main contribution concerning the M-OAN and MM-OAN is just providing new network architectures which are at the beginning stage of this research. However, the performance analyses of both the proposed OAN structures using a modified version of the LS algorithm provide better results than those of the S-OAN and it proves that the research direction with the M-OAN and MM-OAN is on the right way. That is why, the future research demands to give more emphasis in providing a new DBA algorithm for the M-OAN and MM-OAN for getting better performances.

This thesis accentuates on several network architectures of PON-based hybrid networks and DBA algorithms. The main intentions of these proposals in this thesis are to provide a suitable network architecture and DBA algorithm for the PON-based hybrid networks that will be deployed in the over populated areas of some developing countries, e.g., Bangladesh, India, Pakistan etc., where the network cost per user will be less and provided that the better QoSs will be guaranteed. The simulation results prove that the proposed structures and DBA schemes provide better performances and QoSs than the existing schemes. However, the objectives of this research will be fulfilled if it is practically implemented for serving the poor and low income level people. Therefore, the author of this thesis expects that in the near future this research outcome will be implemented and the people of the over populated areas of the underdeveloped countries will be benefited.

References

[1] http://www.ehow.com/about_6495481_hybrid-networks_.html\

[2] H. Shinohara, "FTTH experiences in Japan," IEEE/OSA Journal of Optical Networking (JON), pp. 616-623, June 2007.

[3] H. Mukai, T. Yokotani, T. Kida, "Rapid growth of FTTH by use of PON in Japan, Globecomm 2007.

[4] M. Chowdhury, Y. Jang, and Z. Haas, "Network evolution and QoS provisioning for integrated femtocell/ macrocell networks" AIRCC International Journal on Wireless & Mobile Networks (IJWMN), vol. 2, no. 3, pp.01-16, August 2010.

[5] J. Rosenberg, H. Salama, and M. Squire, "RFC 3219 – Telephony Routing over IP (TRIP)," Jan. 2002, http://www.ietf.org/rfc/rfc3219.txt.

[6] D. Ferrari,"RFC 1193 – Client requirements for real-time communication services," Nov. 1990, http://www.ietf.org/rfc/rfc1193.txt.

[7] M. Younis, M. Youssef, and K. Arisha, "Energy-aware Management in Cluster-based Sensor Networks," Computer Networks 43(5), pp. 649-668, 2003.

[8] S. Bandyopadhyay and E. J. Coyle, "An Energy Efficient Hierarchical Clustering Algorithm for Wireless Sensor Networks," In Proceedings of the INFOCOM 2003, Vol. 3, 1713-1723, (2003).

[9] O. Younis, S. Fahmy, "HEED: A Hybrid Energy-Efficient Distributed Clustering Approach for Ad Hoc Sensor Networks," IEEE Transactions on Mobile Computing 3(4) pp. 366-379, 2004.

[10] T. Dam and K. Langendoen, "An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks," The First ACM Conference on Embedded Networked Sensor Systems (Synsys'03), Los Angeles, CA, USA, November 2003.

[11] J. Tang, X. Jin, Y. Zhang, X. Zhang, and W. Cai, "A hybrid radio over fiber wireless sensor network architecture," Proc. 3rd International Conference on Wireless Communications, Networking and Mobile Computing,WiCom2007, Shanghai, China, pp.2675-2678, Sept. 2007.

[12] M. Hossen, K. Kim, and Y. Park, "Efficient clustering algorithm for delay sensitive PON-based wireless sensor network," Proc. 9th International Conference on Optical Internet (COIN), The Shilla Jeju, Korea, pp.341-343, July 2010.

[13] M. Hossen, Ki-Doo Kim, and Youngil Park, "A PON-based Large Sensor Network and Its Performance Analysis with Sync-LS MAC Protocol" Springer, Arabian Journal for Science and Engineering, Vol.38, issue 8, pp. 2115-2123, August 3013.

[14] IEEE Draft P802.3ah^{TM}/D1.2, "Media access control parameters, physical layers and management parameters for subscriber access networks," December 2002, http://grouper.ieee.org/groups/802/3/efm.

[15] M. McGarry, M. Reisslein, and M. Maier, "Ethernet passive optical network architectures and dynamic bandwidth allocation algorithms," In the proceedings of the IEEE Communications Surveys & Tutorials, vol.10, no.3, pp.46-60, 3rd Quarter 2008.

[16] Document of AKARI project group sponsored by NICT, "New generation network architecture AKARI conceptual design (ver.2, August 2009)," Available: http://akari-project.nict.go.jp/eng/index2.htm.

[17] G. Kramer, B. Mukherjee, and G. Pessavento, "IPACT: A dynamic protocol for an Ethernet PON (EPON)," IEEE Communication Magazine, vol. 40, no. 2, pp. 74-80, 2002.

[18] M. Hossen and M. Hanawa, "Dynamic bandwidth allocation algorithm with proper guard time management over multi-OLT PON-based hybrid FTTH and wireless sensor networks," IEEE/OSA Journal of Optical Communication and Networking (JOCN), vol. 5, no. 7, pp. 802-812, July 2013.

[19] M. Hossen and M. Hanawa, "Adaptive Limited DBA Algorithm for Multi-OLT PON-Based FTTH and Wireless Sensor Networks" In the Proceeding of the 18th IEEE Asia Pacific Conference on Communications (APCC2012), pp. 372- 377, Jeju Island, Korea, October 2012.

[20] M. Hossen and M. Hanawa, "Network Architecture and Performance Analysis of Multi-OLT PON for FTTHs and Wireless Sensor Networks," AIRCC International Journal on Wireless & Mobile Networks (IJWMN), vol. 3, no. 6, pp.01-15, December 2011.

[21] M. Hossen, M. Hanawa, "Adaptive Limited Dynamic Bandwidth Allocation Scheme to Improve Bandwidth Sharing Efficiency in Hybrid PON Combining FTTH and Wireless Sensor Networks" IEICE Transaction on Communication, Vol. E96-B, no.1, pp.127-134, January 2013.

[22] M. Tanaka, T. Nishitani, H. Mukai, S. Kozaki, and H. Yamanaka, "Adaptive Dynamic Bandwidth Allocation Scheme for Multiple-Service in 10G-EPON System," In the Proceeding of IEEE International Conference on Communications, ICC 2011, Kyoto, Japan, June 2011.

[23] G. Kramer and B. Mukherjee, "Ethernet PON: Design and Analysis of an Optical Access Network," Photonic Network Communication, Vol. 3, no. 3, pp. 307-319, 2001.

[24] G. Kramer, B. Mukherjee, S. Dixit, Y. Ye, R. Hirth, "On supporting Differentiated Classes of Service in Ethernet Passive Optical Networks," IEEE/OSA Journal of Optical Networks (JON), vol.1, no.8, pp 280-298, 2002.

[25] G. Kramer, "Ethernet Passive Optical Networks," 1st Ed., McGraw-Hill communications Engineering Series, 2005.

[26] Y. Luo and N. Ansari, "Bandwidth allocation for Multiservice Access on EPONs" New Jersey Institute of Technology IEEE Optical Communication, February, 2005.

[27] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W. Weiss, "An architecture for differentiated services," IETF, RFC 2475, Dec. 1998.

[28] B. Lung "PON architecture 'futureproofs' FTTH", Lightwave, PennWell, vol. 16, no. 10, pp.104 – 107, September 1999.

[29] C. Assi, Y. Ye, S. Dixit, M. Ali, "Dynamic Bandwidth Allocation for Quality-of-Service Over Ethernet PONs," IEEE Journal on Selected Areas in Communications, vol. 21, no.9, pp. 1467-1477, 2003.

[30] A. Banerjee, Y. Park, F. C. H. Song, S. Yang, G. Kramer, K. Kim, B. Mukherjee, "Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review [invited]," IEEE/OSA Journal of Optical Networking (JON), vol. 4, no. 11, pp. 737-758, November 2005.

[31] Y. Hsueh, M. Rogge, W. Shaw, S. Yamamoto, and L. Kazovsky, "Quality of service support over SUCCESS-DWA: a highly evolutional and cost-effective optical access network," In the proceeding of Optical Fiber Communication Conference, Anaheim, California, 6-11 March 2005.

[32] M. McGarry, M. Maier, and M. Reisslein, "An evolutionary WDM upgrade for EPONs," Technical Report, Arizona State University, 2005.

[33] ITU-T G.984.x Series of Recommendations; http://www.itu.int/rec/T-REC-G/e.

[34] Y. Hotta, A. Tsuji, K. Sugimura, S. Kozaki, N. Suzuki, J. Nakagawa, K. Shimokasa, "The demonstration of symmetric 10G-EPON system for coexistence with 1G-EPON," In the proceeding of Optical Fiber Communication Conference, San Diego, CA, pp. 01-03, March 2009.

[35] M. Hajduczenia, H. J. A. d. Silva, and P. P. Monteiro, "EPON versus APON/GPON: A detailed performance comparison," IEEE/OSA Journal of Optical Networking (JON), vol. 5, no. 4, pp. 298-319, 2006.

[36] B. Skubic, J. Chen, J. Ahmed, L. Wosinska, B. Mukherjee, "A comparison of dynamic bandwidth allocation for EPON, GPON, and next-generation TDM PON," IEEE Communication Magazine, vol. 47, pp. S40-S48, March 2009.

[37] F. Effenberger, K. McCammon, and V. O'Byrne, "Passive optical network deployment in North America," IEEE/OSA Journal of Optical Networking (JON), vol. 6, no. 7, pp. 808-818, July 2007.

[38] F. Effenberger, H. Ichibangase, H. Yamashita, "Advances in broadband passive optical networking technologies," IEEE Communication Magazine, vol. 39, no. 12, pp. 118-124, December 2001.

[39] E. Trojer, S. Dahlfort, D. Hood, and H. Mickelsson, "Current and next-generation PONs: A technical overview of present and future PON technology," Ericsson Review, no. 2, pp. 64-69, 2008.

[40] F. Aurzada, M. Scheutzow, M. Reisslein, N. Ghazisaidi, and M. Maier, "Capacity and delay analysis of next-generation passive optical networks (NG-PONs)," IEEE Transactions on Communications, vol. 59, no. 5, pp. 1378-1388, May 2011.

[41] IEEE 802.3, "Call for interest: 10Gb/s PHY for EPON, 2006"; http://www.ieee802.org/3/cfi/0306_1/cfi_0306_1.pdf.

[42] R. Lin, "Next generation PON in emerging networks," in the proceeding of OFC/NFOEC, pp. 1-3, San Diego, CA, February 2008.

[43] Next-Generation PON Evolution, http://www.huawei.com/en/static/hw-077443.pdf.

[44] K. Son, H. Ryu, S. Chong, T. Yoo, "Dynamic bandwidth allocation schemes to improve utilization under nonuniform traffic in Ethernet passive optical networks," in the proceedings of IEEE International Conference on Communications, vol. 3, pp.1766-1770, June 2004.

[45] J. Zheng, "Efficient bandwidth allocation algorithm for Ethernet passive optical networks," in the proceedings of IEE Proceedings Communications, Vol. 153, no. 3, pp. 464-468, June 2006.

[46] B. Chen, J. Chen, S. He, "Efficient and fine scheduling algorithm for bandwidth allocation in Ethernet passive optical networks," IEEE Journal of Selected Topics in Quantum Electronics, vol. 12, no. 4, pp. 653-660, 2006.

[47] X. bai, A. Shami, C. Assi, "On the fairness of dynamic bandwidth allocation schemes in Ethernet passive optical networks," Computer Communications, vol. 29, no. 11, pp. 2123-2135, 2006.

[48] N. Sadek, A. Khotanzad, "A dynamic bandwidth allocation using a two-stage fuzzy neural network based traffic predictor," in the proceedings of IEEE International Conference on Neural Networks, vol. 3, pp. 2407-2412, July 2004.

[49] M. Wu, R. A. Joyce, H. S. Wong, L. Guan, S. Y. Kung, "Dynamic resource allocation via video content and short-term traffic statistics," IEEE Transactions on Multimedia, vol. 3, no. 2, pp. 186-199, 2001.

[50] N. Sadek, A. Khotanzad, T. Chen, "ATM dynamic bandwidth allocation using F-ARIMA prediction model," in the proceedings of 12th International Conference on Computer Communications and Networks, pp. 359-363, October 2003.

[51] Y. Luo, N. Ansari, "Limited sharing with traffic predication for dynamic bandwidth allocation and QoS provisioning over Ethernet passive optical networks," IEEE/OSA Journal of Optical Networking (JON), vol. 4, no. 9, pp. 561-572, 2005.

[52] I. Hwang, Z. Shyu, L. Ke, C. Chang, "A novel early DBA mechanism with prediction-based fair excessive bandwidth allocation scheme in EPON," Elsevier Journal of Computer Communications, vol. 31, no. 9, pp. 1814-1823, June 2008.

[53] IEEE Standard 802.3ah-2004.

[54] Virtual Bridged Local Area Networks, IEEE Standard 802.IQ, 1998.

[55] W. Willinger, M. Taqqu, R. Sherman, and D. V. Wilson, "Self-similarity through high variability: statistical analysis of Ethernet LAN traffic at the source level," IEEE/ACM Trans. Networking, vol. 5, pp. 71-86, 1997.

[56] S. Ostring and H. Sirisena, "The influence of long-range dependence on traffic prediction," In the proceedings of the IEEE International Conference on Communications'2001, pp.1000-1005, 2001.

[57] I. Norros, "On the use of fractional Brownian motion in the theory of connectionless networks," IEEE Journal on Selected Areas Communications, vol. 13, no. 6, pp. 953-962, August 1995.

[58] A. Dhaini, C. Assi, M. Maier, and A. Shami, "Dynamic wavelength and bandwidth allocation in hybrid TDM/WDM EPON networks," IEEE/OSA Journal of Light-wave Technology, vol. 25, no. 1, pp. 277-286, January 2007.

[59] K. Kwong, D. Harle, and I. Andonovic, "Dynamic bandwidth allocation algorithm for differentiated services over WDM EPONs," In the proceedings of the 9th IEEE International Conference on Communication Systems (ICCS), pp. 116-120, September 2004.

[60] M. McGarry, M. Maier, and M. Reisslein, "WDM Ethernet passive optical networks," IEEE Communication Magazine, vol. 44, no. 2, pp. S18-S25, February 2006.

[61] A. Dhaini, C. Assi, and A. Shami, "Quality of service in TDM/WDM Ethernet passive optical networks (EPONs)," In the proceedings of the 11th IEEE Symposium on Computers and Communications 2006 (ISCC '06), pp. 616-621, June 2006.

[62] G. Kramer, B. Mukherjee, and G. Pesavento, "Interleaved polling with adaptive cycle time (IPACT): A dynamic bandwidth distribution scheme in an optical access network," Photonic Network Communication, vol. 4, no. 1, pp. 89-107, 2002.

[63] L. Kazovsky, W. Shaw, D. Gutierrez, N. Cheng, and S. Wong, “Next-generation optical access networks,” IEEE Journal of Lightwave Technology, vol. 25, no. 11, pp. 3428-3442, November 2007.

[64] W. Willinger, M. S. Taqqu, and A. Erramilli, “A bibliographical guide to self-similar traffic and performance modeling for modern high-speed networks, stochastic networks: theory and applications,” Royal Statistical Society Lecture Notes Series, Oxford University Press, Oxford, U.K., vol. 4, pp. 339-366, 1996.

[65] K. Park, and W. Willinger, “Self-similar network traffic and performance evaluation,” A Wiley-Interscience Publication, John Wiley & Sons, Inc., 2000.

[66] X. Bai, and A. Shami, “Modeling self-similar traffic for network simulation,” Technical report, NetRep-2005-01, 2005.

[67] B. Mandelbrot, “How Long Is the Coast of Britain? Statistical Self-Similarity and Fractional Dimension,” Science Magazine, vol.156, no.3775, pp. 636-638, May 1967.

[68] W. Leland, M. Taqqu, W. Willinger, and D. Wilson, “On the self-similar nature of Ethernet traffic,” IEEE/ACM Transactions on Networking, vol.2, no.1, February 1994.

[69] H. Fowler, W. Leland, and B. Bellcore, "Local Area Network Traffic Characteristics, with Implications for Broadband Network Congestion Management", IEEE Journal on Selected Areas in Communications, vol.9, no.7, pp.1139-1149, September 1991.

[70] B. Lannoo, L. Verslegers, D. Colle, M. Pikavet, P. Demeester, and M. Gagnaire, “Thorough analysis of the IPACT dynamic bandwidth allocation algorithm for EPONs,” In the proceedings of the 4th International Conference on Broadband Communications, Networks and Systems, pp. 486-494, 2007.

[71] V. Rajendran, K. Obraczka, and J.J. Garcia-Luna-Aceves, “Energy-efficient, collision-free medium access control for wireless sensor networks,” Journal of Wireless Networks, vol.12, no.1, pp. 63-78, 2006.

[72] M. Forzati, C. Larsen, and C. Mattsson, “Open access networks, the Swedish experience,” In the proceedings of the 12th International Conference on Transparent Optical Networks (ICON), PP. 01-04, June 27-July 1, 2010.

[73] M. Matson, and R. Michell, “Study on local open access networks for communities and municipalities,” ICT Regulation Toolkit, March 2006. Available online: http://www.ictregulationtoolkit.org/en/toolkit/docs/Document/3368.

[74] “Introducing the open access network,” Telephony Online, June 9, 2004. Available online: http://telephonyonline.com .

[75] PMC-Sierra, PAS6300 Product Brief. Available online: http://pmcs.com/products/optical_networking/ftth_pon/epon/pas6300/.

[76] M. Guizani, A. Rayes, A. Al-Fuqaha, "Link sizing for multi-media traffic transported over IP," Cluster Computing, vol. 4, pp. 335-342, October 2001.

[77] H. Uzawa, K. Terada, N. Ikeda, A Miyazaki, M. Urano, and T. Shibata, "Energy-efficient frame-buffer architecture and it's control schemes for ONU power reduction," In the proceedings of the Global Telecommunications Conference GLOBECOM 2011, pp. 01-05, December 2011.

List of Publications

Journals:

1. **Monir Hossen** and Masanori Hanawa, "Dynamic bandwidth allocation algorithm with proper guard time management over multi-OLT PON-based hybrid FTTH and wireless sensor networks," IEEE/OSA Journal of Optical Communication and Networking (JOCN), vol. 5, no. 7, pp. 802-812, July 2013.
2. **Monir Hossen**, Masanori Hanawa, "Adaptive Limited Dynamic Bandwidth Allocation Scheme to Improve Bandwidth Sharing Efficiency in Hybrid PON Combining FTTH and Wireless Sensor Networks" IEICE Transaction on Communication, Vol. E96-B, no.1, pp.127-134, January 2013.
3. **Monir Hossen** and Masanori Hanawa, "Network Architecture and Performance Analysis of Multi-OLT PON for FTTHs and Wireless Sensor Networks," AIRCC International Journal on Wireless & Mobile Networks (IJWMN), vol. 3, no. 6, pp.1-15, December 2011.

International Conferences:

1. **Monir Hossen** and Masanori Hanawa, "Adaptive Limited DBA Algorithm for Multi-OLT PON-Based FTTH and Wireless Sensor Networks" In the Proceeding of the 18th IEEE Asia Pacific Conference on Communications (APCC2012), pp. 372- 377, Jeju Island, Korea, October 2012.
2. Hayato Uematsu, **Monir Hossen**, Koji Nonaka, Y. Choi, C.-S. Park, Masanori Hanawa, "Low-Time-Jitter and Wavelength-tunable Short Optical Pulse Source Using Reflective Semiconductor Optical Amplifier as Gain Medium" In the Proceeding of Asia-Pacific Microwave Photonic Conference (APMP2012), Kyoto, Japan, April 2012.
3. Hayato Uematsu, **Monir Hossen,** Kazuki Hashiguchi, Koji Nonaka, Masanori Hanawa, "VCSEL-based Gain-Switching Short Optical Pulse Source with Time-Jitter Suppression by Self-Seeding Method," In the Proceeding of the 17th IEEE Microoptics Conference (MOC'11), Sendai, Japan, November 2011.
4. Masanori Hanawa and **Monir Hossen,** "Experimental Investigation on Spectrum Scrambling of UWB-IR Signals Using High-speed Optical 2×2 Switch" In the Proceeding of IEEE International Topical Meeting on Microwave Photonics, Singapore, October 2011.

Domestic Conferences:

1. **Monir Hossen**, Masanori Hanawa, "Multi-OLT and Multi-wavelength PON for Improving QoS of Open Access Network" In the Proceeding of IEICE Society Conference, Fukuoka, Japan, September 2013.
2. **Monir Hossen**, Masanori Hanawa, "A New Dynamic Bandwidth Allocation Algorithm for Multi-OLT PON-Based FTTH and Wireless Sensor Networks" In the Proceeding of IEICE General Conference, Gifu, Japan, March 2013.
3. **Monir Hossen** and Masanori Hanawa, "Performance Enhancement of Open Access Network by Employing Multi-OLT PON" In the Proceeding of IEICE Society Conference, Toyama, Japan, September 2012.
4. **Monir Hossen** and Masanori Hanawa, "Adaptive Limited Dynamic Bandwidth Allocation Algorithm for PON-based FTTH and Wireless Sensor Networks," In the Proceeding of IEICE General Conference, Okayama, Japan, March 2012.
5. **Monir Hossen** and Masanori Hanawa, "Network Architecture and Interleaved Polling Algorithm for Multi-OLT PON Based FTTH and Wireless Sensor Network" In the Proceeding of IEICE Society Conference, Hokkaido, Japan, September 2011.

Abbreviations

ALDBA	Adaptive Limited Dynamic Bandwidth Allocation
ALDBAM	Adaptive Limited Dynamic Bandwidth Allocation Algorithm for Multi-OLT PON
AP	Access Point
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BMU	Buffer Management Unit
CDR	Clock and Data Recovery
CH	Cluster Head
CO	Central Office
DBA	Dynamic Bandwidth Allocation
EBR	Excessive Bandwidth Realocation
E-DBA	Early Dynamic Bandwidth Allocation
EO	Ethernet Overhead
FIFO	First-in First-out
FBA	Fixed Bandwidth Allocation
FN	Femto Network
FRTT	Fluctuation of Round Trip Time
FSAN	Full Service Access Network
FTTH	Fiber-to-the-home
G	Gate Message
Gbps	Giga bit per second
GEM	General Encapsulation Method
GI	Guard Interval
GPON	Gigabit PON
HDTV	High Definition Television
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
I/O	Input/Output

IPACT	Interleaved Polling with Adaptive Cycle Time
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication
LAN	Local Area Network
LP	Linear Predictor
LRD	Long Range Dependence
LS	Limited Service
LSTP	Limited Sharing with Traffic Prediction
MAC	Medium Access Control
MM-OAN	Multi-OLT and Multi-wavelength PON-based Open Access Network
M-OAN	Multi-OLT PON-based Open Access Network
MP2P	Multi-point to Point
MPCP	Multi Point Control Protocol
ms	milli-second
NID	Node Identification
NGPON	Next Generation PON
OAN	Open Access Network
OLT	Optical Line Terminal
ONT	Optical Network Terminal
ONU	Optical Network Unit
P2MP	Point to Multi-point
PANC	Personal Area Network Coordinator
PFEBA	Prediction-based Fair Excessive Bandwidth Allocation
PON	Passive Optical Network
QoS	Quality of Service
R	Report Message
RF	Radio Frequency
RN	Remote Node
RoF	Radio over Fiber
RTT	Round Trip Time
SC	Service Code
S-OAN	Single-OLT PON-based Open Access Networks

TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
u-City	Ubiquitous City
UID	User Identification
VoD	Video on Demand
VoIP	Voice over Internet Protocol
VS	Versus
WDM	Wavelength Division Multiplexing
WSN	Wireless Sensor Network