國立交通大學

電信工程學系

碩士論文

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基於效用函數的乏晰波長分配

Utility-based Fuzzy Wavelength Assignment in OBS Network

研 究 生：林和儁
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Abstract

光群集交換(Optical Burst Switching, OBS)是一個充滿前景的技術，它利用了光通訊的優點以及資料流的多工處理使得它成為一個適合在全光網路環境下使用的技術。光群集交換不僅利用了光通訊的優點以及多工處理，更靠著它本身特殊的傳輸機制；控制封包(Control burst)以及推移時間(Offset time)來幫助它有效的提升資料吞吐量。雖然光群集交換可以有效的提升資料吞吐量，但當同時有多個控制封包預約的時間是重疊的，便會發生競爭進而導致資料的遺失也使得資料吞吐量降低。因此，適當而有效的波長分配演算法在提升光群集交換的資料吞吐量中扮演著重要的角色。

在本篇論文中，我們提出了基於效用函數上的乏晰波長分配演算法，此方法引入了四個重要的參數：替代指數、使用的光纖延遲線長度、空隙長度以及波長利用率，並利用了效用函數和乏晰邏輯系統的結合來改進光群集交換網路中的資料吞吐量。除此之外，由於傳輸服務品質(Quality of Service)也是光群集交換網路中所注重的議題，我們所提出的乏晰波長分配演算法也能夠在不同的訊務種類中支援傳輸服務品質。

Utility-based Fuzzy Wavelength Assignment in OBS Network

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Abstract

Optical Burst Switching (OBS) is a promising technology that exploits the benefits of optical communication and supports statistical multiplexing of data traffic at a fine granularity making it a suitable technology for the all optical network. The characteristic of the OBS is using the control bursts (CBs) and the offset time mechanism to make bandwidth reservations without ACKs. Although the characteristic of OBS can help improve utilization, contention among the data bursts (DBs) that arrive simultaneously at a core node leads to burst loss and low throughput. Development of efficient algorithms for wavelength assignment is crucial to utilize wavelengths more efficiently so that we can improve the throughput in OBS networks. In this paper, we will propose the utility-based fuzzy wavelength assignment (UFWA) to improve the throughput in the OBS network by introducing the four factors, including preemption index, the used length of the FDL, void, and utilization and using the combination of the utility function and the fuzzy logic system. Moreover, the proposed UFWA can support quality-of-Service (QoS) between different traffic types, while the QoS is also the main issue in the OBS network.

誌　謝

本篇論文的完成，首先要感謝張仲儒教授在學術論文上的悉心指導，以及在做人處事集人生規劃上的諄諄教誨，讓我在兩年的研究生中找到自己未來努力的目標。也要感謝不辭辛勞犧牲，在自己忙於研究之下，還能撥冗指導的文祥學長，以及雖然在不同領域的研究，但是還是相當熱心提供研究的寶貴經驗的文敬學長、志明學長、耀興學長和振宇學長。在實驗室的生活中，除了學長們提供了寶貴的研究經驗，也感謝實驗室的大家在生活上和課業上給予我的諸多協助。兩年的碩士班研究生涯轉瞬即逝，但其中許多的歡笑和辛苦讓我想起仍十分感動而快樂。從碩士班一年級剛進來實驗室熱情歡迎我們的尚樺學長、宗利學長、邱胤學長、英奇學長、浩翔學長、維謙學長和巧瑩學姐；研究過程中一起辛苦的志遠、欣毅和盈仔；還有努力帶給我們歡樂，減輕我們研究壓力的學弟妹正忠、蕊綺、耀庭、心瀅、以芾，以及從旁協助我們各樣事務的助理玉棋。因為有大家的陪伴，在課業上一起討論，生活上一同分享，度過許許多多無論是快樂的抑或是充滿淚水的時光，讓這兩年研究生活增添了更多回憶。很開心身為寬頻通訊研究室的一份子，祝福實驗室的大家學業順利，事事順心。

最後，謹以此篇論文獻給我最摯愛的父母和弟弟，以及所有一直以來關心、支持我的親友們。

林和儁　謹誌

2009 年 7 月

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Chapter 1
Introduction

The rapid growth of the internet has resulted in an increasing demand for the transmission capacity in the core networks. As the capabilities of electronic switching and traditional transmission techniques cannot satisfy the request, the core networks should evolve new architectures based upon all optical switching and dense wavelength division multiplexing (DWDM) technologies due to the high transmission capacity of optical fibers [1-6]. Three kinds of optical switching, optical circuit switching (OCS), optical packet switching (OPS), and optical burst switching (OBS), are proposed to fully utilize the huge bandwidth of optical fibers [2-6].

In an OCS network, a light path would be set up when a new call connection request arrives. The light path between the source and destination nodes of the new call is only provided for the new call. However, the light path occupies a single wavelength. The low bandwidth utilization is the disadvantage of the OCS, because the average required bandwidth of a call is always less than the capacity of a wavelength [2-4].

In an OPS network, a packet would be split into two parts, the header and the data, when the packet arrives. The header of the packet would first pass through optical-to-electronic (O/E) conversion to let an OPS node decide a route for the packet, and then the node would generate a new header of the packet and passes it through electronic-to-optical (E/O) conversion. Finally, the new header of the packet would be combined with the data of the packet. Thus, a disadvantage of the OPS is the long processing time to deal with the header, and a challenge of the OPS is the packets synchronizers. Also, when the OPS node processes the header of the packet, the data of the packet is stored in the fiber delay line (FDL). Therefore, the OPS requires a lot of the FDLs [2, 3, 5].

In an OBS network, an ingress node assembles the packets with the same characteristics, such as quality-of-service (QoS), requirement, and destination, into a data burst (DB) and generates an associated control burst (CB). The CB will be sent to next node, passing a control channel, to reserve the bandwidth for the DB. Without acknowledgement, the DB will be sent, passing a data channel, after an offset time, as the CB is sent out. The duration of the offset time is related with the routing path of the DB, which is decided in the ingress node. The OBS can improve the utilization of the network, comparing with the OCS, because a wavelength does not be occupancied by a connection; the OBS can to reduce the processing time of the header, comparing with the OPS, because a burst contains a number of packets. Therefore, the OBS is attracting more and more attentions of many researchers and institutes, and it is considered as a promising paradigm for building the next generation optical network [2, 3, 6].

A number of signaling protocols have been proposed for OBS, a just-in-time (JIT), a just-enough-time (JET), a prioritized just-enough-time (PJET), and a preemptive prioritized just-enough-time (PPJET) [3, 7, 8, 9]. The two former signaling protocols do not consider the quality-of-service, but the two latter ones are provided for the QoS provisioning. The JIT is an immediate signaling protocol while the JET is a delayed signaling protocol, but the JET has better performance in burst loss probability [7, 8]. The main drawback of the PJET is that it introduces a significant amount of delay for high-priority traffic in order to provide a reasonable isolation level from lower-priority traffic classes [3, 9]. Without the excessive delay, however, the PPJET allows the higher priority bursts preempting the lower priority bursts, on the basis of a strict priority order, even the lower priority bursts have been assigned the wavelengths [9].

While more than one DB could be destined to go out of the same output port (wavelengths) at the same time, the contention among the DBs will lead to burst losses. Thus, many wavelength assignment methods are proposed to resolve the problem under the different signaling protocols [10, 11, 12]. These three wavelength assignment methods, Horizon [10], the latest available unscheduled channel (LAUC) [11], and the LAUC with void filling (LAUC-VF) [12], are proposed under the JET signaling protocol. They all could use the FDLs to help reduce burst losses whereas the LAUC-VF can achieve the higher bandwidth utilization and the lower burst loss rate [12]. The preemptive latest available unused channel with void filling (PLAUC-VF) was another wavelength assignment method provided but it worked under PPJET signaling protocol [9].

A new wavelength assignment method, called utility-based fuzzy wavelength assignment (UFWA), is proposed in this paper. The UFWA is designed, using the fuzzy logics, to utilize wavelengths more efficiently. It would lower the length of preempted bursts and use the shorter FDL if needed, and reduce the void between the DBs as possible to achieve its goal. The four parameters of a wavelength are considered: the preemption index, the length of the used FDL, the utilization ratio during an observing window, and the length of the void between the observing DB and its succeeding scheduled DB on the wavelength. The UFWA contains three kinds of components: a suitable wavelength concentrator (SWC), a fuzzy wavelength evaluator (FWE), and a wavelength selector (WS). The SWC would choose the several more suitable wavelengths with the higher utilities from the all wavelengths. The FEW would decide an adequate degree of a chosen wavelength. The WS compares the adequate degrees of the chosen wavelengths and chooses one wavelength which is with the highest degrees. Finally, the UFWA assign this wavelength to the DB.

The rest of the paper is organized as follows. First, developing a system model in chapter 2. Then introducing how the UFWA works to assign the most suitable wavelength for DBs in chapter 3. Chapter 4 will shows the simulation results compared with other algorithms. Finally chapter 5 is the conclusion.

Chapter 2
System Model

2.1 The Architecture of OBS Networks

An optical burst switching (OBS) network contains edge nodes and core nodes, shown in Fig.1. An edge node could be an ingress (source) node or egress (destination) nodes. In the ingress node, the packets with the same characteristics, such as destinations and QoS requirements, would be assembled into a data burst (DB), using an appropriate burst assembly algorithm, and the node would also generate an associated control burst (CB) of the DB [13, 14]. In the egress node, a DB would be disassembled into these packets. The burst assembly algorithms contain three major categories: time-based, volume-based, and hybrid algorithms. In the time-based algorithm, when a packet arrives at an empty assembly buffer, an associated timer would be set to zero and start. Then, as the timer reaches a time threshold, all packets stored in the assembly buffer are aggregated into a DB. In the volume-based algorithm, all packets of an assembly buffer are aggregated into a DB if the occupancy of the assembly buffer reaches or is larger than a volume threshold after a new packet is stored in the buffer. Alternatively, in the hybrid assembly algorithm, when a timer reaches the time threshold or the occupancy of an assembly buffer reaches or exceeds the volume threshold, all packets stored in the associated assembly are aggregated into a DB. That is, a DB will be generated when either the timer goes off or the volume threshold is exceeded.

The CB contains the control signaling information, such as the destination, the burst length, the wavelength on which the DB will arrive, the offset time between the CB and DB, and the priority level etc. The CB is used to make wavelength reservation on each node of the associated DB's routing path which is decided in the ingress node. It is sent to the next node to reserve bandwidth for its associated DB and the DB would be also sent after an offset time whose duration is dependent on the total number of intermediate nodes in the DB's routing path. If the reservation is fail at a node, the associated DB would be dropped at this node. There are totally W+1 wavelengths (channels) in each fiber link. One of these wavelengths is called the control channel which is used to transit the CBs; the others are called the data channels which are used to transit the DBs.

Several signaling protocols are proposed to help the core node to reserve the wavelength for a DB when its associated CB arrives at the node [7, 8]. There is no acknowledgement in these signaling protocols, so the DB would be transited by cut-through switching at core nodes without optical-to-electronic-to-optical (O/E/O) conversions. One of the signaling protocols is the immediate scheme, called Just-in-Time (JIT). The JIT contains two kinds of the bandwidth releases method: the explicit release method and the estimated release method [15]. The main difference between these two methods is that the explicit release method needs another control message to inform the next node to release the reserved channel, whereas the estimated release method does not, shown in the Fig. 2.

Another protocol is a delay scheme, called Just-Enough-Time (JET). The difference between the JIT and JET is that a node only reserves a fixed duration on a wavelength for a DB when its associated CB arrives. The duration starts at the arrival time of the DB and its length is equal to the length of the DB, shown in the Fig. 3. Apparently, the JET utilizes wavelengths more efficiently than the other two versions of JIT. However, the JET does not provide the different service requirements, thus the PJET and the PPJET are proposed. The PJET is based on the JET but it will let the burst with higher priority has an extra offset time, and this extra offset time will let the burst has more chance to make a reservation successfully. The PJET will be showed in Fig. 4. However, the extra offset time will also cause a large time delay to the higher priority traffic. Because of the drawback of the PJET, PPJET is proposed to use a priority value to represent a DB's importance. Also, if a burst with the higher priority cannot find an available wavelength to assign on, the burst can preempt a burst with the lower priority which has been assigned, shown in Fig. 5. To avoid a longer time delay for the bursts with higher priority, this paper will use the PPJET as the signaling protocol to support class differentiation in this paper instead of PJET.

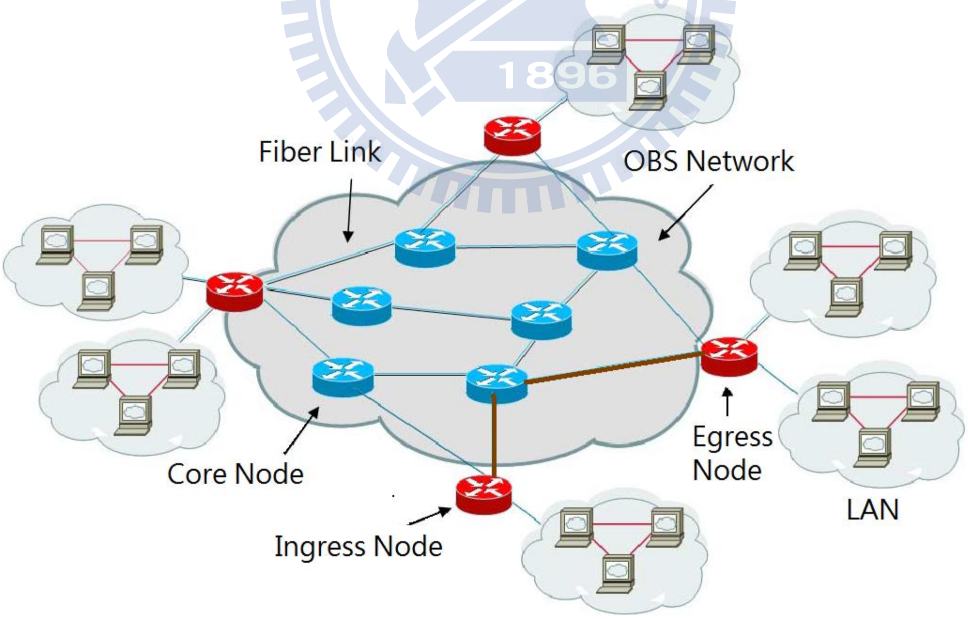

Fig. 2.1 The architecture of the OBS

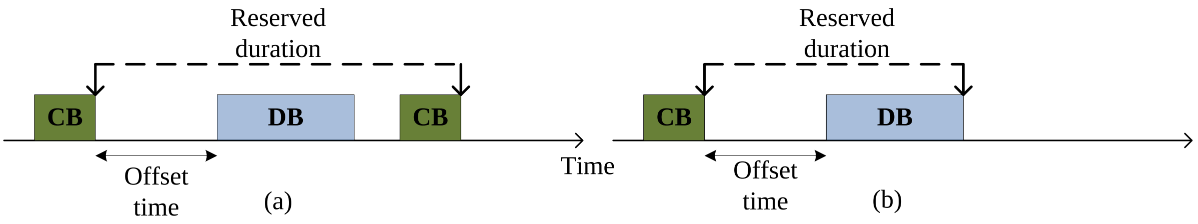

Fig. 2.2 (a) explicit release JIT (b) estimated release JIT

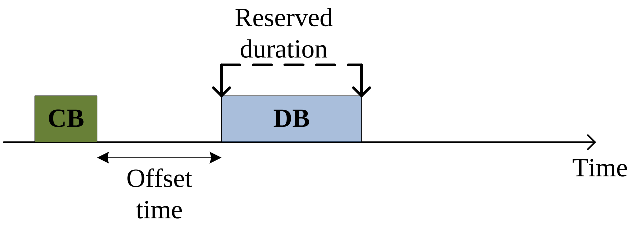

Fig. 2.3 JET protocol

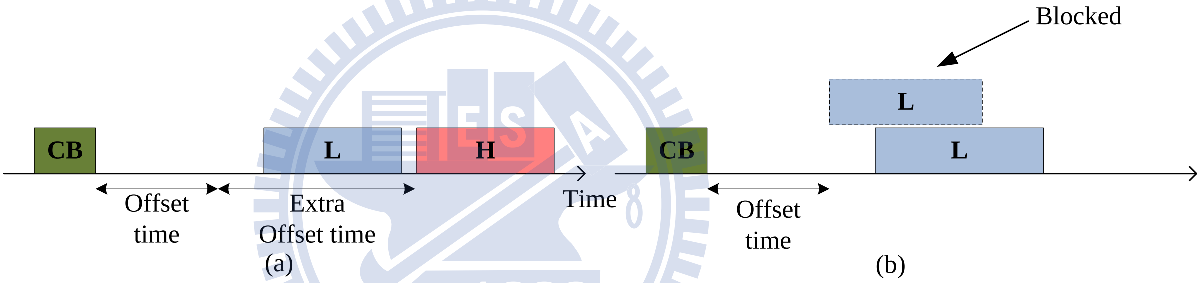

Fig. 2.4 PJET (a) the DB with higher priority has an extra offset time (b) the DB with lower priority does not have an extra offset time

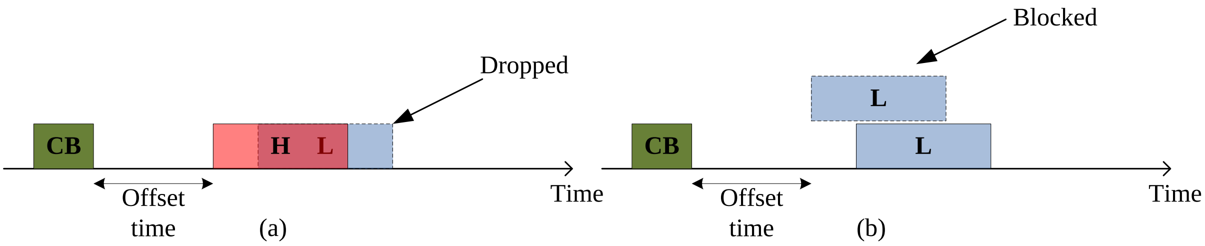

Fig. 2.5 PPJET (a) the DB with higher priority preempts the DB with lower priority (b) the DB with lower priority cannot preempt any DBs

2.2 The Architecture of OBS Nodes

An OBS node connects other *N* OBS nodes. Each fiber contains *W* data channels transmitting DBs and one control channel transmitting CB. Therefore, there are totally

W+ 1 wavelengths (channels) in each fiber. The architecture of an OBS node, shown in the Fig. 6, consists of a receiver equipment (RX), a transmitter equipment (TX), *N* input fiber delay lines (FDLs), *N* wavelength convertors (WCs), a *N*W-by-*N*W non-blocking optical switching matrix (OSM), one optical-to-electronic (O/E) conversion, one electronic-to-optical (E/O) conversion, and a central processor (CP) containing the utility-based fuzzy wavelength assignment (UFWA). The RX receives a DB from a data channel and forwards it to the input FDLs if the DB could be scheduled into an available channel; otherwise, the RX drops it. Also, the RX receives CBs from a control channel and forwards them to the central processor. In the same way, the TX transmits DBs (CBs) into data (control) channels. The input FDLs consists of a number of FDLs with different units of length. The WC transfers the DB from the original wavelength to the destined wavelength decided by the central processor.

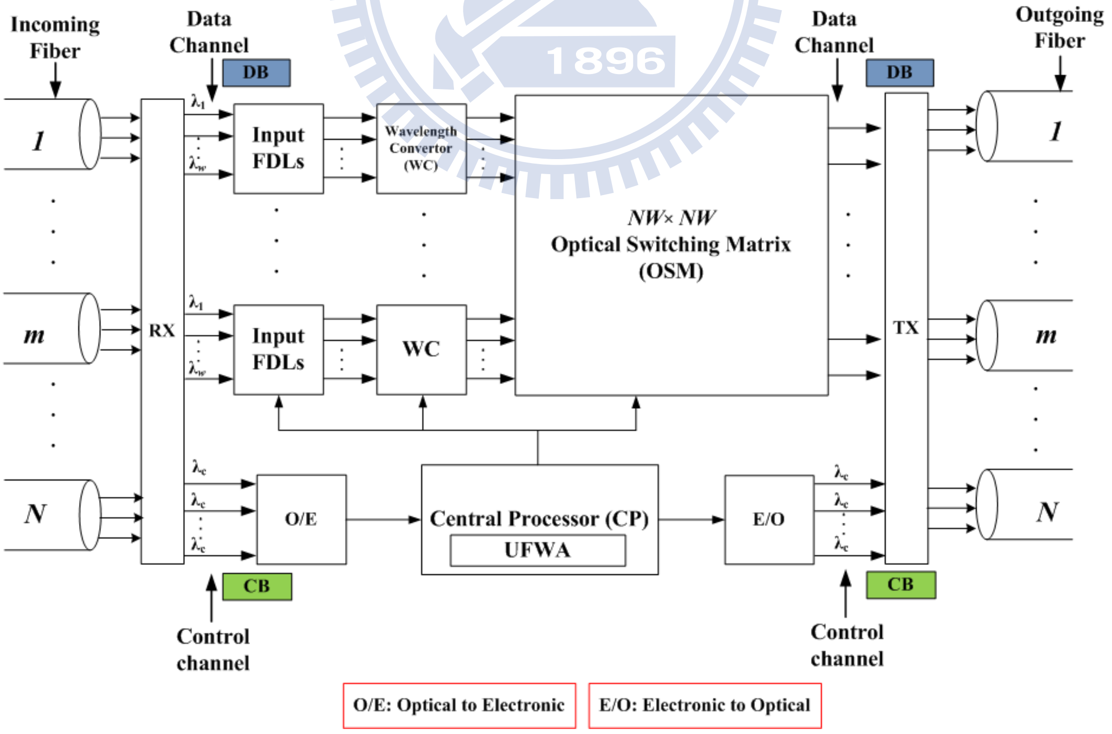

Fig. 2.6 The architecture of OBS nodes

The central processor (CP) uses the utility-based fuzzy wavelength assignment

(UFWA) to reserve a suitable wavelength for a DB when the associated CB arrives. The result of the wavelength assignment would be sent to input FDLs, WCs and the OSM to inform which FDL would be used for the DB, which wavelength would be assigned for the DB and which output fiber would be used to transform the DB. Also, the CP would regenerate an associated CB for the DB according to the result of the wavelength assignment. The new CB would be sent to the next node.

Chapter 3

Utility-based Fuzzy Wavelength Assignment (UFWA)

An intelligent wavelength assignment algorithm, called fuzzy wavelength assignment (FWA), is designed to decide the most suitable wavelength and FDL if needed for a DB when its associated CB arrives at an OBS node. The FWA wants to utilize wavelengths more efficiently by lowering the occurrence of preemptions and using the shorter FDL if needed. The FWA is a three-stage process, consisting of a suitable wavelength concentrator (SWC), the M fuzzy wavelength evaluators (FWEs), and a wavelength selector (WS), shown in the Fig. 3.1. The SWC is designed to choose only M adequate wavelengths from W wavelengths based on their own utilities which are related with the preemption indexes, denoted by R, the lengths of the used FDL, denoted by F, the utilization over an observing window, denoted by U, and the ratio of the time gap over the average DB length, denoted by G. The four parameters could be obtained from the length of the DB, denoted by B, the arrival time of the DB, denoted by T_a, and the priority value of the DB, denoted by P. The FWEs evaluate the M wavelength's adequate degrees, denoted by A, using fuzzy logics. The WS choose a wavelength with the highest adequate degree, from the M wavelengths, as the most suitable wavelength, denoted by w_x, to be assigned for the DB. Thus, the FWA would inform the WC and OSM which wavelength is assigned to the DB, and schedule the corresponding FDL, denoted by F_x, to the DB.

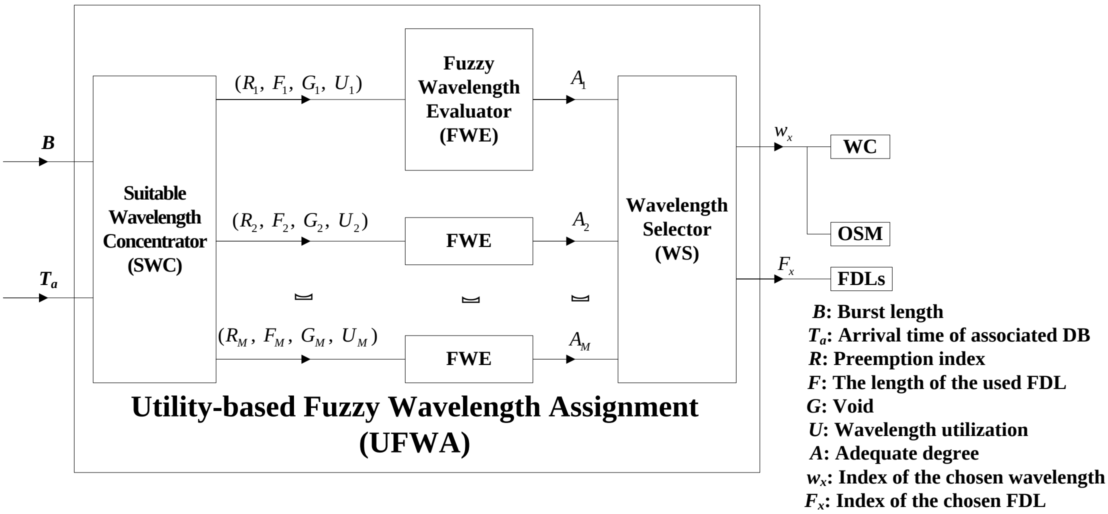

Fig. 3.1 Utility-based fuzzy wavelength assignment (UFWA)

3.1 Suitable Wavelength Concentrator (SWC)

The SWC chooses only M adequate wavelengths from W wavelengths to limit the number of the FWEs for reducing the cost and computation of the FWA. The inputs of the SWC are the length, and the arrival time of the DB, which are denoted by B, and T_a, respectively. The SWC would pre-assign the DB on each wavelength and thus calculate the associated utility according to the result of the pre-assignment of the wavelength which is represented by itself four parameters: the preemption index, the length of the used FDL, the utilization over an observing window, and the ratio of the time gap over the average DB length. Afterward, the SWC selects the M wavelengths whose utilities are the larger M ones. Next, how to obtain the four parameters on the w^{th} wavelength is introduced as follows.

The preemption index on the w^{th} wavelength, denoted by R_w, could be obtained by

$$R_w = 0.1 \cdot \frac{B_1 + B_2 + \cdots + B_q}{B}, \quad R_w \in (0, \infty] \tag{3.1}$$

where q is the number of the preempted DBs by the associated DB if the associated

DB is scheduled on this wavelength, and B_i is the length of the i^{th} preempted burst, for $i = 1, 2, \ldots, q$. When there exists an unused FDL which is used to delay the DB if the DB is scheduled on this wavelength, the length of the used FDL on the w^{th} wavelength is denoted by F_w. The utilization over an observing window on the w^{th} wavelength, denoted by U_w, could be obtained by

$$U_w = B_{total} / (B + K), \qquad U_w \in (0,1] \tag{3.2}$$

where K is the longest length of FDLs, and B_{total} is the sum of the burst lengths of the assigned DBs in the observing window whose time interval starts from the arrival time, T_a, and its length is B+K. The ratio of the time gap on the w^{th} wavelength, denoted by G_w, is a normalized value which is obtained by dividing the time gap over the average DB length. The time gap is the duration between the DB and a reserved DB whose arriving time is close to the DB and earlier than the DB.

The process of the SWC on the i^{th} wavelength is described in detail as follows:

Step 1: [Schedule without FDL and preemption]

If the time interval, $[T_a, T_a + B]$, on the i^{th} wavelength is available for the DB, the four parameters of this wavelength are $(0, 0, U_i, G_i)$ and then go to *step* 4. If not, then go to *step* 2.

Step 2: [Schedule with FDL but without preemption]

If j is not larger than K and it is the smallest unused FDL such that the time interval, $[T_a + jD, T_a + B + jD]$, on this wavelength is available for the DB, where D is the unit length of the FDLs, the four parameters of the wavelength are $(0, j, U_i, G_i)$ and then go to *step* 4. If there is no the unused FDL which is suitable for the DB, go to *step* 3.

Step 3: [Schedule without FDL but with preemption]

If the priority value of the associated DB is larger than each of the priority values of the assigned DBs whose reserved time duration, $[T_a, T_a + B]$, the four parameters of the wavelength are (R_i, 0, U_i, G_i), and then go to *step* 4. If not, the four parameters of the wavelength are (-1, -1, -1, -1), and then go to *step* 4.

Step 4: [Calculate the utility of this wavelength]

The utility of this wavelength is related with the evaluation functions of the four parameters and could be obtained by

$$u_i = \begin{cases} f_R \cdot f_F^{rt} \cdot f_G \cdot f_U, & if \text{ real time traffic,} \\ f_R \cdot f_F^{nrt} \cdot f_G \cdot f_U, & if \text{ non real time traffic,} \end{cases} \tag{3.3}$$

where f_R , f_U, and f_G are the evaluation functions of preemption index, the utilization over an observing window, and the ratio of the time gap over the average DB length, respectively, and f_R^{rt}, f_R^{nrt} are the real-time and non-real-time evaluation function of the length of the used FDL. When the utility of each wavelength is calculated, the SWC will sort them. The M wavelengths with the higher M utilities are chosen and their four parameters are in order denoted by (R_1, F_1, U_1, G_1), (R_2, F_2, U_2, G_2), …, (R_w, F_w, U_w, G_w). Next, these five evaluation functions are described as follows. The evaluation function of preemption index is defined as:

$$f_R = \begin{cases} 4, & if \ R_w = 0, \\ -0.2R_w + 1, & if \ 0 < R_w \le 1, \\ 0.8e^{-(R_w-1)^3}, & if \ R_w > 1. \end{cases} \tag{3.4}$$

Note that the large number of the preempted DBs increases the blocking probability. The sum length of the preempted DBs is too larger than the DB's length to increase the bandwidth utilization but is smaller to enhance the bandwidth utilization. Therefore, the evaluation function of preemption index decreases linearly when R_w is smaller than one, and decreases exponentially when R_w is larger than one.

The real-time and non-real-time evaluation function of the length of the used FDL is defined as follows:

$$f_F^{rt} = \begin{cases} 2.5, & if\ F_w = 0, \\ -0.5\dfrac{F_w}{K} + 1.5, & if\ F_w \neq 0 \\ 0, & if\ F_w > \lfloor \gamma \cdot K \rfloor, \end{cases} \tag{3.5}$$

and

$$f_F^{nrt} = \begin{cases} 2.5, & if\ F_w = 0, \\ -0.5\dfrac{F_w}{K} + 1.5, & if\ F_w \neq 0. \end{cases} \tag{3.6}$$

The reason is that the real-time bursts are delay-sensitive, so they cannot be delayed for a long time. Also, the evaluation function of the utilization over an observing window is defined as follows:

$$f_U = 0.47e^{{U_w}^6} + 0.53. \tag{3.7}$$

It is because that the DB is priori to be assigned a wavelength with high utilization if there is an available unreserved duration of this wavelength for the DB.

The evaluation function of the ratio of the time gap over the average DB length is defined as follows:

$$f_G = 0.5 \cdot e^{-G_w} + 1. \tag{3.8}$$

The reason is that a smaller void is hard to be filled by another burst. However, if the void is very large, it is easy to be filled up by another burst. Therefore, the evaluation function will first decrease deeply and then decrease slowly.

3.2 Fuzzy Wavelength Evaluator (FWE)

The FWE uses the fuzzy logic system to decide an adequate degree of each wavelength from the chosen M wavelengths. Other than the utility function, the FWE can help define a more specific adequate degree using several logic rules. Notice that the inputs of the FEW is the four parameters of the w^{th} chosen wavelength, R_w, F_w, U_w, and G_w, and the output of the FEW is an adequate degree of the wavelength, denoted by A_w. Once using the fuzzy logic system, we can not only make difference between several situations by many logic rules but also define thresholds which are used to classify the fours parameters' level. Define the term set with four terms for R_w as $T(R_w)$ = {*Null* (*Nu*), *Low* (*Lo*), *Medium* (*Me*), *High* (*Hi*)}, where the term "*Null*" means no preemption occurs, and the terms from "*Low* " to "*High* "mean the utilization becomes from better to worse, respectively. The term set with three terms for F_w as $T(F_w)$ = {*None* (*No*), *Short* (*S*), *Long* (*L*)}, where the term "*None*" means there is no FDL used. The term set with two terms for U_w as $T(U_w)$ = {*Small* (*Sm*), *Large* (*La*)}. The term set with two terms for G_w as $T(G_w)$ = {*Narrow* (*Na*), *Wide* (*Wi*)}. The term set with twelve terms for A_w as $T(A_w)$ = {$Level_1$ (L_1), $Level_2$ (L_2), $Level_3$ (L_3), $Level_4$ (L_4), $Level_5$ (L_5), $Level_6$ (L_6), $Level_7$ (L_7), $Level_8$ (L_8), $Level_9$ (L_9), $Level_{10}$ (L_{10}), $Level_{11}$ (L_{11}), $Level_{12}$ (L_{12}) , $Level_{13}$ (L_{13}) , $Level_{14}$ (L_{14}) , $Level_{15}$ (L_{15}) , $Level_{16}$ (L_{16}) , $Level_{17}$ (L_{17}) , $Level_{18}$ (L_{18}) , $Level_{19}$ (L_{19}) , $Level_{20}$ (L_{20})}.

The membership functions of these terms should be defined with the proper shape and position. Generally speaking, a trapezoidal function or a triangular function is used to be the membership functions because they are suitable for real-time application. The two functions $Tri(x;\ a,\ b,\ c)$ and $Trap(x;\ a,\ b,\ c,\ d)$ are given by

$$Tri(x;\ a,\ b,\ c)=\begin{cases}\dfrac{x-a}{b-a}, & for\ a< x\le b,\\ \dfrac{c-x}{c-b}, & for\ b< x<c,\\ 0, & otherwise,\end{cases} \tag{3.9}$$

$$Trap(x;\ a,\ b,\ c,\ d)=\begin{cases}\dfrac{x-a}{b-a}, & for\ a<x<b,\\ 1, & for\ b<x<c,\\ \dfrac{d-x}{d-c}, & for\ c<x<d,\\ 0, & otherwise,\end{cases} \tag{3.10}$$

where arguments, a, b, c in $Tri(\cdot)$ are three vertexes of the triangular function from left to right; arguments, a, b, c, d in $Trap(\cdot)$ are four vertexes of the trapezoidal function from left to right.

The membership functions for terms *Nu*, *Lo*, *Me*, and *Hi* in $T(R_w)$ are defined as

$$\mu_{Nu}(R_w) = Tri(R_w;\ 0,\ 0,\ 0), \tag{3.11}$$

$$\mu_{Lo}(R_w) = Trap(R_w;\ 0,\ 0,\ t_1^R,\ t_2^R), \tag{3.12}$$

$$\mu_{Me}(R_w) = Tri(R_w;\ t_3^R,\ t_4^R,\ t_5^R), \tag{3.13}$$

$$\mu_{Hi}(R_w) = Trap(R_w;\ t_6^R,\ t_7^R,\ \infty,\ \infty), \tag{3.14}$$

where t_i^R, for i=1, 2, …, 7, is a threshold. Let $\mu_{Term}(F_w)$ denote the membership functions for terms *Nu*, *S*, *L* in $T(F_w)$ and define them as

$$\mu_{No}(F_w) = Tri(F_w;\ 0,\ 0,\ 0), \tag{3.15}$$

$$\mu_{S}(F_w) = Trap(F_w;\ 0,\ 0,\ t_1^F,\ t_2^F), \tag{3.16}$$

$$\mu_{L}(F_w) = Trap(F_w;\ t_3^F,\ t_4^F,\ K,\ K), \tag{3.17}$$

where t_i^F, i =1, 2, 3, 4, denote thresholds. The membership functions associated with the terms *Sm* and *La* in $T(U_w)$ are $\mu_{Sm}(U_w)$ and $\mu_{La}(U_w)$, respectively and are given by

$$\mu_{Sm}(U_w) = Trap(U_w;\ 0,\ 0,\ t_1^U,\ t_2^U), \tag{3.18}$$

$$\mu_{La}(U_w) = Trap(U_w;\ t_3^F,\ t_4^F,\ 1,\ 1), \tag{3.19}$$

where t_i^U, i=1, 2, 3, 4, denote thresholds. The membership functions associated with the terms *Na* and *Wi* in $T(G_w)$ are $\mu_{Na}(G_w)$ and $\mu_{Wi}(G_w)$, respectively and are given by

$$\mu_{Na}(G_w) = Trap(G_w;\ 0,\ 0,\ t_1^G,\ t_2^G), \tag{3.20}$$

$$\mu_{Wi}(G_w) = Trap(G_w;\ t_3^G,\ t_4^G,\ \infty,\ \infty), \tag{3.21}$$

where t_i^G, i=1, 2, 3, 4, denote thresholds. Finally, the membership function associated with the terms L_i in $T(A_w)$ is formulated as a fuzzy singleton, and it is

$$\mu_{L_i}(A_w) = Tri(A_w;\ t_i^A,\ t_i^A,\ t_i^A), \tag{3.22}$$

where $t_i^A = \dfrac{i}{20}$, for i =1, 2, …, 12. The membership function of each fuzzy term set is shown in the Fig. 5.

According to above defined fuzzy sets, the fuzzy rule is constructed in Table 3.1. There are 20 fuzzy logic relationships in a form of "if-then" rules between 18 input linguistic variables and 12 output linguistic variables. Generally, we will give higher degree to the wavelength with the lower preemption index, the shorter length of the used FDL, the larger utilization, and the narrower gap.

The FWE acquires the four input linguistic terms from the fuzzifier and adopts the *max-min* inference method to obtain the output linguistic term. In Table 3.1, for example, rule 9th and rule 13th lead to the same result, L_{12}. For obtaining the output membership values of "$T(A_w)$ is L_{12}", the inference engine applies the *min* operation on membership values of 9th and 13th rules, which are denoted as m_9 and m_{13}, respectively.

$$m_9 = \min(\mu_{Nu}(R_w),\ \mu_L(F_w),\ \mu_{Na}(G_w),\ \mu_{La}(U_w)), \tag{3.23}$$

$$m_{13} = \min(\mu_{Lo}(R_w),\ \mu_{No}(F_w),\ \mu_{Na}(G_w),\ \mu_{La}(U_w)). \tag{3.24}$$

Next applying the *max* operation between m_9 and m_{13} yields the overall membership value of control action "$T(A_w)$ is L_{12}" by

$$M_{L_{12}} = \max(m_9,\ m_{13}). \tag{3.25}$$

Similarly, the other eleven output membership values of control actions: M_{L_1}, M_{L_2}, M_{L_3}, …, $M_{L_{11}}$ and $M_{L_{12}}$ can be obtained. After inferring all rules, using the *center of* *area* defuzzifcation strategy generates an overall A_w as follows:

$$A_w = \frac{\sum_{i=1}^{20} t_i^A \cdot M_{L_i}}{\sum_{i=1}^{20} M_{L_i}}, \tag{3.26}$$

where t_i^A is the fuzzy singlton value corresponding to the output fuzzy term set.

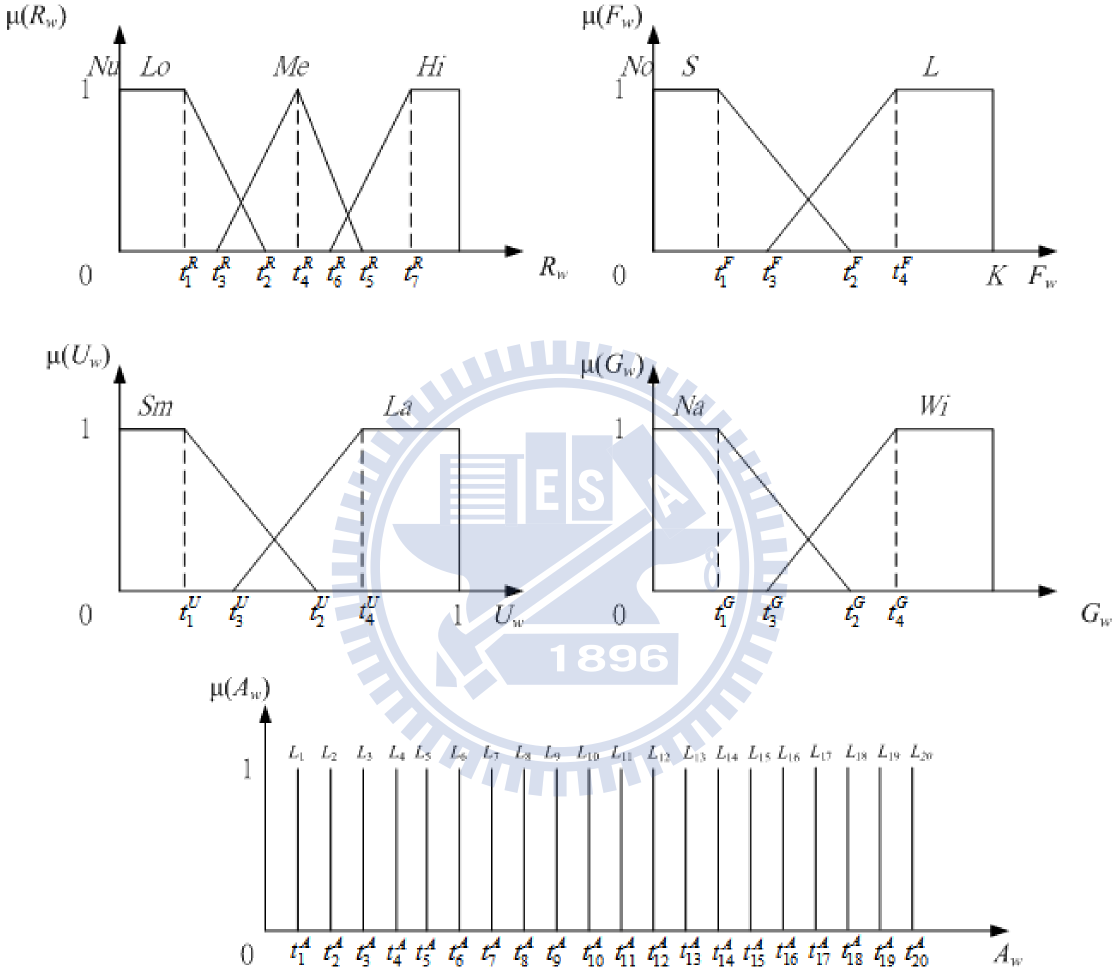

Fig. 3.2 Fuzzy member functions

Table 3.1 Fuzzy rules

rule	T(R_w)	T(F_w)	T(G_w)	T(U_w)	T(A_w)	**rule**	T(R_w)	T(F_w)	T(G_w)	T(U_w)	T(A_w)
1	*Nu*	*No*	*Na*	*La*	L_{20}	**13**	*Lo*	*No*	*Na*	*La*	L_{12}
2	*Nu*	*No*	*Na*	*Sm*	L_{19}	**14**	*Lo*	*No*	*Na*	*Sm*	L_{11}
3	*Nu*	*No*	*Wi*	*La*	L_{18}	**15**	*Lo*	*No*	*Wi*	*La*	L_{10}
4	*Nu*	*No*	*Wi*	*Sm*	L_{17}	**16**	*Lo*	*No*	*Wi*	*Sm*	L_9
5	*Nu*	*S*	*Na*	*La*	L_{16}	**17**	*Me*	*No*	*Na*	*La*	L_8
6	*Nu*	*S*	*Na*	*Sm*	L_{15}	**18**	*Me*	*No*	*Na*	*Sm*	L_7
7	*Nu*	*S*	*Wi*	*La*	L_{14}	**19**	*Me*	*No*	*Wi*	*La*	L_6
8	*Nu*	*S*	*Wi*	*Sm*	L_{13}	**20**	*Me*	*No*	*Wi*	*Sm*	L_5
9	*Nu*	*L*	*Na*	*La*	L_{12}	**21**	*Hi*	*No*	*Na*	*La*	L_4
10	*Nu*	*L*	*Na*	*Sm*	L_{11}	**22**	*Hi*	*No*	*Na*	*Sm*	L_3
11	*Nu*	*L*	*Wi*	*La*	L_{10}	**23**	*Hi*	*No*	*Wi*	*La*	L_2
12	*Nu*	*L*	*Wi*	*Sm*	L_9	**24**	*Hi*	*No*	*Wi*	*Sm*	L_1

3.3 Wavelength Selector (WS)

The WS will choose the wavelength with the largest degree among the A_i, for i = 1, 2, …, M. And then the WS will inform the WC and OSM which wavelength is assigned to the DB, and schedule the corresponding FDL, denoted by F_x, to the DB.

Chapter 4
Simulation Results and Discussion

4.1 Simulation Environment

The link capacity of each fiber is 10 Gbps, and each fiber has 8 wavelengths (*W*=8). Therefore, each wavelength has the transmission rate equivalent to 1.25 Gbps. In order to support QoS, there are two kinds of traffic types, including the real time traffic and the non real time traffic. The real time traffic has its own delay sensitive nature, so it cannot wait for a long time to aggregate a large burst. Thus, the real time traffic would have shorter average burst length than non real time traffic. In the simulation, the average burst length of the real time traffic is 8 μs (equivalent to 10Kb), and the average burst length of the non real time traffic is 32 μs (equivalent to 40Kb). And both the bursts inter-arrival time and the burst lengths follow the Pareto distribution with the parameter k=1.5 [17]. In addition, each incoming burst would have the probability 0.5 to be the real time traffic and the probability o.5 to be the non real time traffic. The number of the remaining hops will be generated uniformly between 1 and 10. And there are 10 different kinds of length of FDLs (*K*=10), where the basic delay time is 10 μs (*D*=10).

4.2 Compared Algorithms

There are two other conventional wavelength assignments used in PPJET [3, 7, 8, 9], called preemptive latest available unused channel with void filling (PLAUCVF) and efficient preemption-based channel scheduling (EPCS). For the case FDLs are not used and preemption does not occur, these two algorithms will first check the duration of [T_a, T_a+B] to find whether the duration is available or not. If the duration, [T_a, T_a+B], is available on several wavelengths, the PLAUC and the EPCS will select the wavelength with the smallest void. If there are two or more wavelengths with the smallest void, the two algorithms will choose one randomly. Once [T_a, T_a+B] is not available on any wavelengths, FDLs would be considered to be used to delay the associated DB. In the case of using FDLs, the two algorithms will find the suitable unused shortest FDL. While there are not any suitable FDLs could be used and the associated DB could preempt some assigned DB, whose reserved durations overlap [T_a, T_a+B], on some wavelengths, the PLAUCVF and the EPCS would choose different wavelengths to assign the associated DB based on their own algorithms. The PLAUCVF would select the wavelength with the smallest void to assign, while the EPCS will choose the wavelength with the smallest length of the preempted bursts from the preemptive region. The PLAUCVF divides all W wavelengths into two parts, called the shard region (contains W-m wavelengths) and the preemptive region (contains m wavelengths). The wavelengths in the shared region will view all kinds of traffic as the same type (which means preemption will not occur in the shared region), while the wavelengths in the preemptive region can still adopt preemption. The following figure 4.1 shows the cases of not using FDLs and using FDLs while preemption does not occur and the figure 4.2 and 4.3 show the cases of preemption.

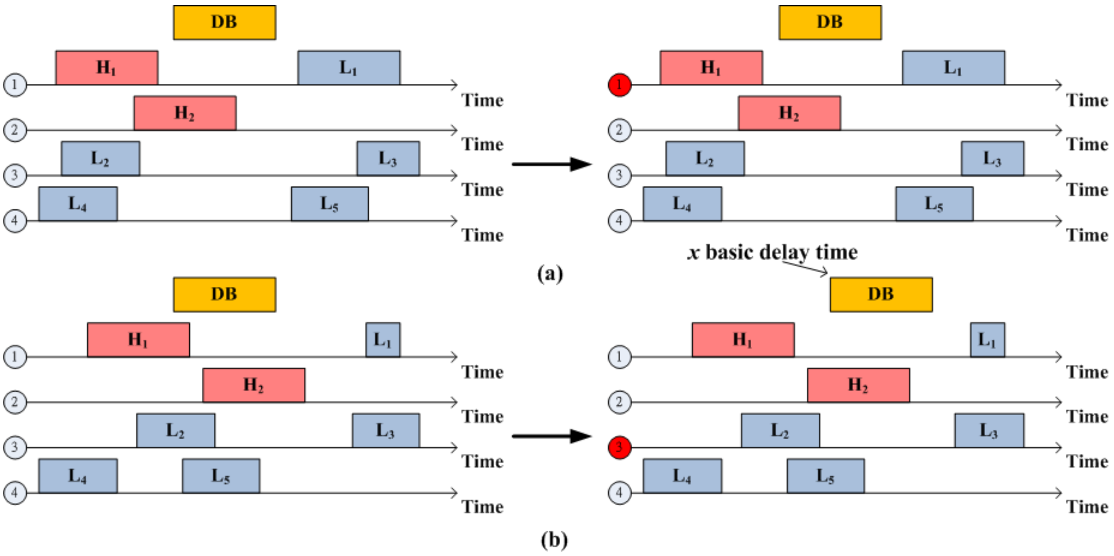

Fig. 4.1 (a) The case of not using any FDLs (b) The case of using a suitable FDL

In the figure 4.1 (a), the associated DB could be assigned on wavelength #1, #3, and #4 without using any FDLs. And the two algorithms would choose the wavelength #1 because it has the smallest void among the others. In the figure 4.1 (b), the associated DB cannot find any available wavelengths at the duration [T_a, T_a+B], so the FDL would be considered. While a suitable unused shortest FDL would be used, the PLAUCVF and the EPCS will choose the wavelength #3 because it has the smallest void among the others.

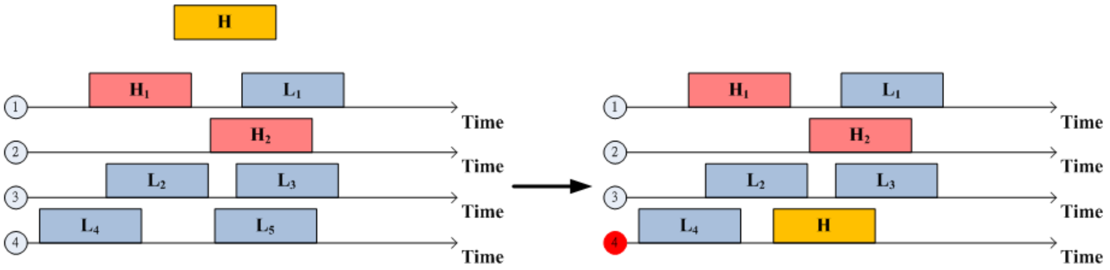

Fig. 4.2 The case of preemption of the PLAUCVF

When there are not any suitable FDLs to be used and the associated DB has the higher priority, the preemption could be adopted. In the figure 4.2, the PLAUCVF could choose either the wavelength #3 or the wavelength #4 because the preemption cannot be adopted on the other two wavelengths due to the same priority. The PLAUCVF would finally select the wavelength #4 due to the smallest void.

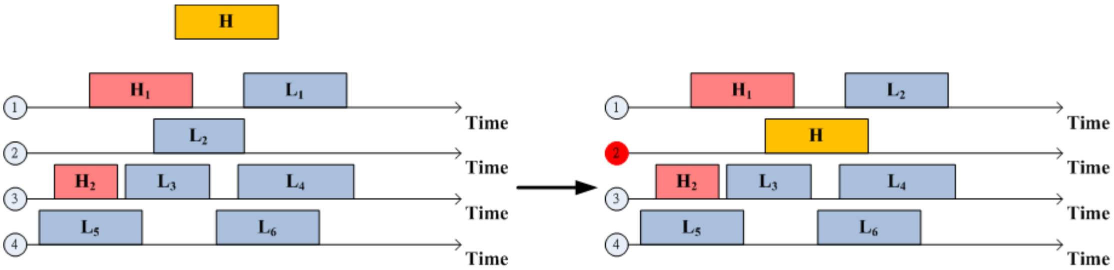

Fig. 4.3 The case of preemption of the EPCS

In the figure 4.3, the EPCS has the preemptive region with the wavelength #1, #2 and #3 and the shared region with the wavelength #4. The EPCS could choose either the wavelength #2 or the wavelength #3 because the preemption cannot be adopted on the other two wavelengths due to the same priority and the shared region scheme. The MPLAUC would eventually select the wavelength #2 due to the smallest length of the preempted bursts.

4.3 Simulation Results

In this section, we will use some figures to show the better performance of the utility-based fuzzy wavelength assignment (UFWA) among the PLAUCVF and the EPCS.

4.3.1 Throughput

Fig. 4.4 illustrates the system throughput versus the traffic load intensity. The traffic load intensity is the normalized traffic by the capacity of each fiber, 10Gbps. It can be found that the throughput is increasing more slowly. It is because when the traffic load intensity is getting larger, the duration of bandwidth requests would overlap more frequently, and FDLs could be not available to delay any DBs anymore. Therefore, there are lots of bursts could be blocked or preempted, and that will lead to much higher burst loss probability (BLP) and lower throughput which is compared to the offered load. Besides, the proposed UFWA would provide higher throughput (when M=4, M=8) than the two compared algorithms, especially at high traffic load intensity (when traffic load intensity equal to 0.8, 0.9 and 1). For example, higher than MPLAUC-VF about 300Mbps and higher than EPCS about 150Mbps at traffic load intensity equal to 1. It is because the UFWA considering about four important parameters, preemption index (R_w), the length of the used FDL (F_w), void (G_w), and utilization (U_w). R_w avoids the occurrences of preemption and longer preemption. F_w , G_w ,and U_w help make wavelengths arranged more tightly. Other than the proposed UFWA, the PLAUCVF and the EPCS choose the shortest FDL to delay the DB while UFWA would make a balance between delays and voids to make wavelength arranged more tightly. Besides, the PLAUCVF does not consider the length of the preempted bursts as a factor, while the EPCS does, and that lead the former one has worse performance than the latter one in throughput. The EPCS uses not only the length of the preempted bursts as the factor but also shared region to protect the longer but lower prioritized DB (non real time traffic in this paper) to make better throughput than the PLAUCVF. As for the utility method, which is used only the utility function to make wavelength assignments, it would avoid choosing the longer FDL to delay the real time traffic due to the delay sensitive nature. Therefore, utility method and even UFWA (*M*=2) would rather select the preemption operation not using longer FDL. That would cause too much preemption to have better throughput.

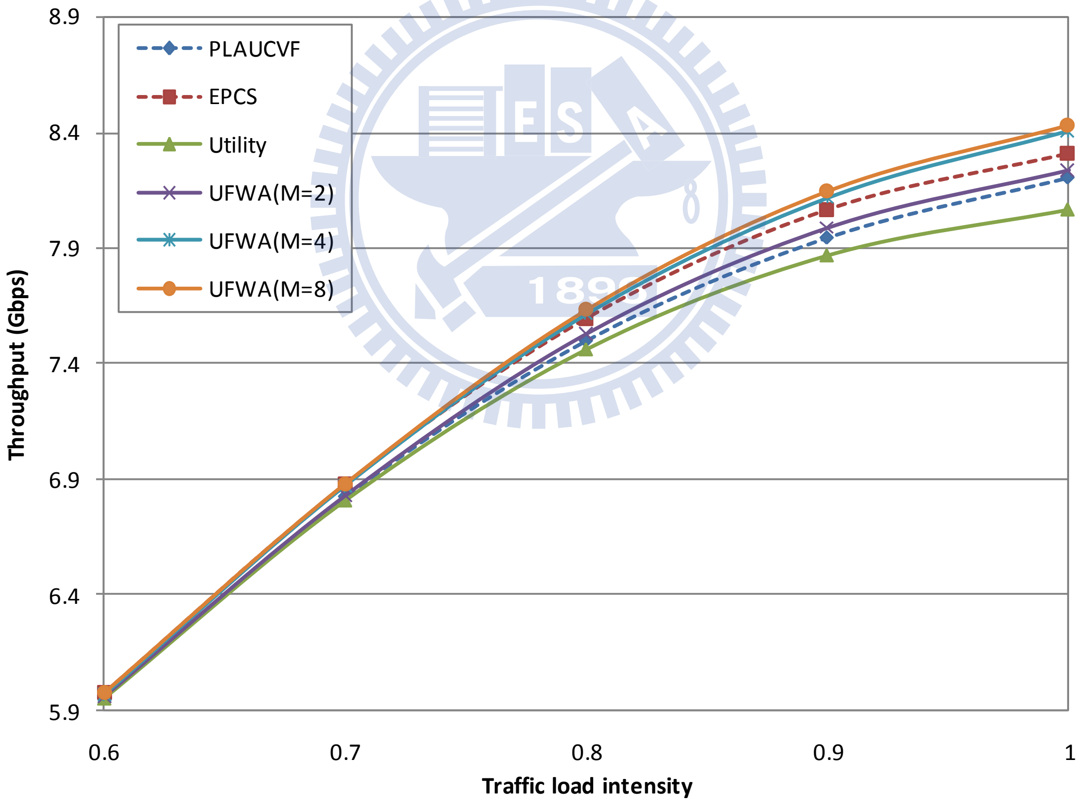

Fig. 4.4 Throughput (Gbps)

4.3.2 Total length of the preempted bursts

Fig. 4.5 shows the total length of the preempted bursts versus the traffic load intensity. It can be found that the total length of the preempted bursts is increasing when the traffic load intensity is getting larger. In addition, the utility method and the UFWA (*M*=2) indeed preempt too much bursts to have a better throughput discussed in the section 4.3.1. The PLAUCVF also preempts longer length because it does not take the preempted length into consideration while the EPCS preempts shorter length.

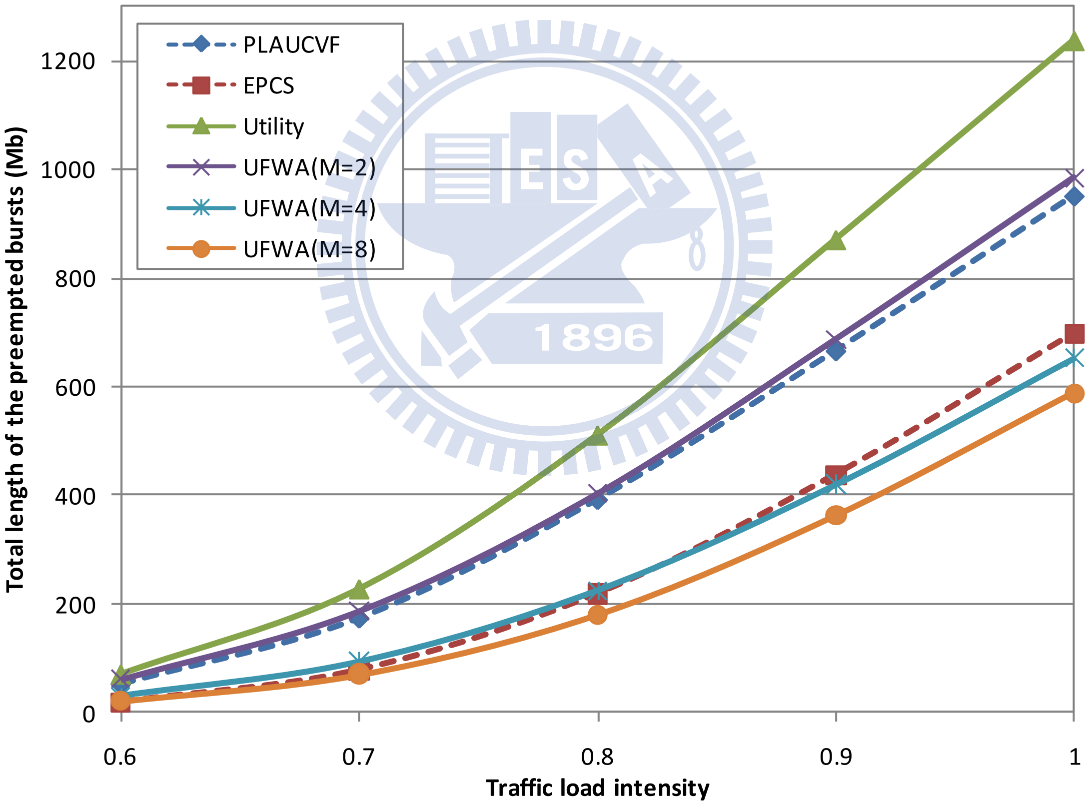

Fig. 4.5 Total length of the preempted bursts

4.3.3 Total length of the blocked bursts

Fig. 4.6 shows the total length of the blocked bursts versus the traffic load intensity. It can be found that the total length of the blocked bursts is increasing when the traffic load intensity is getting larger. In addition, the utility method and the UFWA (*M*=2) block the two shortest bursts length. It is because these two methods preempt too much DBs and that would let wavelengths be more "empty" than the others. Thus, the more empty wavelengths could accept more bandwidth requests. By the way, the UFWA (*M*=4, *M*=8) blocks less length that the EPCS while the EPCS preempts small total length of the DBs as the UFWA (*M*=4), and slightly larger than the UFWA (*M*=8). It is because the UFWA considers preempted length, void, and utilization, and these parameters could make wavelengths arranged more tightly to let future DBs have higher opportunity to make bandwidth reservation.

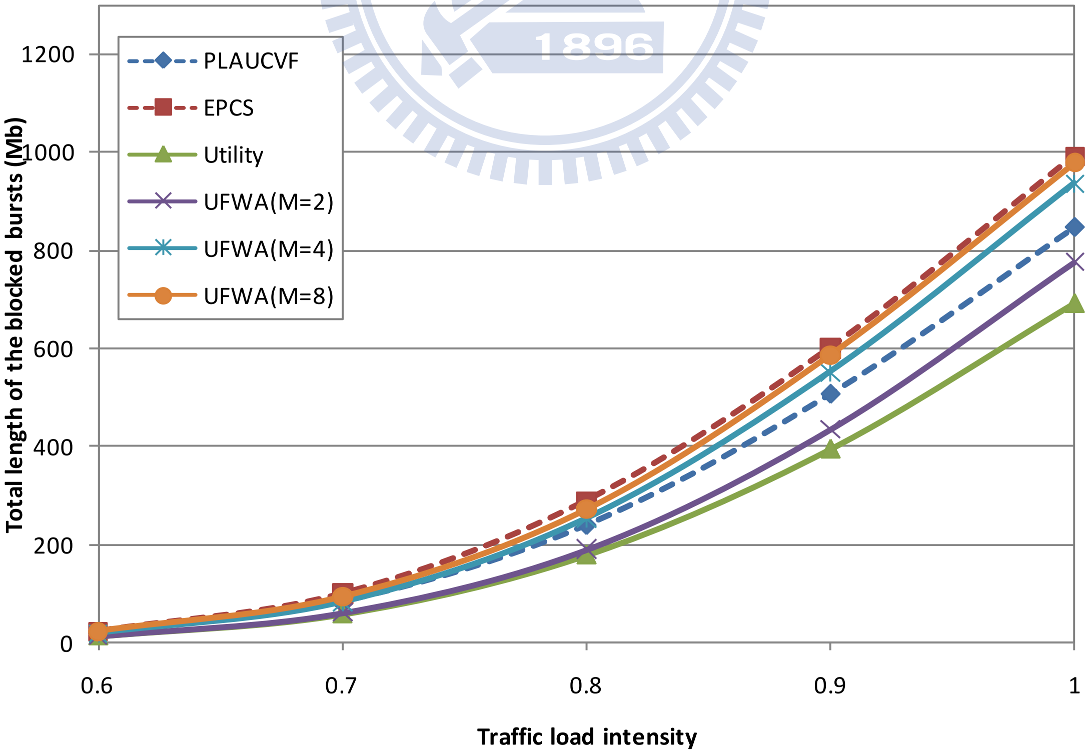

Fig. 4.6 Total length of the blocked bursts

4.3.4 The number of the preempted bursts

Fig. 4.7 shows the number of the preempted bursts versus the traffic load intensity. It can be found that the number of the preempted bursts is increasing when the traffic load intensity is getting larger. In addition, the PLAUCVF and the EPCS have smaller number of the preempted bursts. It is because these two wavelength assignments choose the suitable shortest unused FDL to delay DB, and that would cause larger void while the proposed UFWA could select the slightly longer FDL but make smaller void. In other words, the UFWA makes wavelength arranged more tightly. The UFWA's characteristic lets DBs have higher chance to make bandwidth reservations but larger number of preempted bursts. Once preemption occurs, lots of number DBs could be preempted. But we should notice that the proposed still have higher throughput than the PLUCVF and the EPCS.

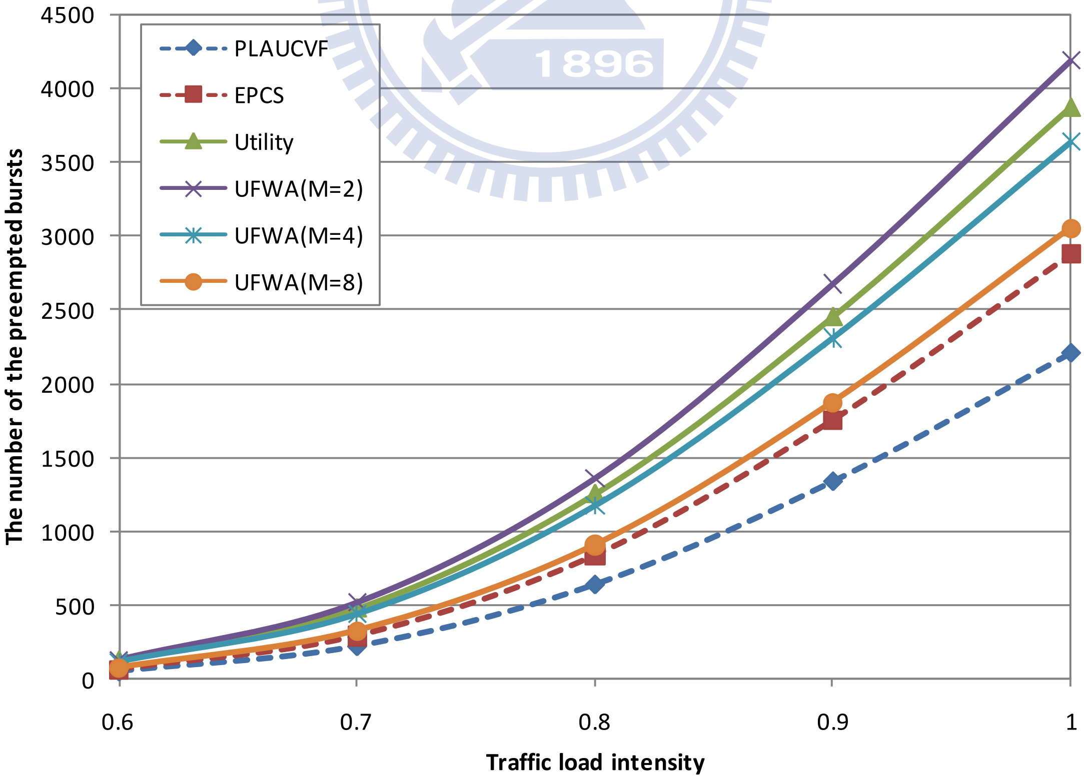

Fig. 4.7 The number of the preempted bursts

4.3.5 The number of the blocked bursts

Fig. 4.7 shows the number of the blocked bursts versus the traffic load intensity. It can be found that the results match the reason in the section 4.3.2. The longer length of the preempted bursts, the higher chance of accepting bandwidth requests. Therefore, the utility method and the UFWA (*M*=2) will have the two smallest number of the blocked bursts.

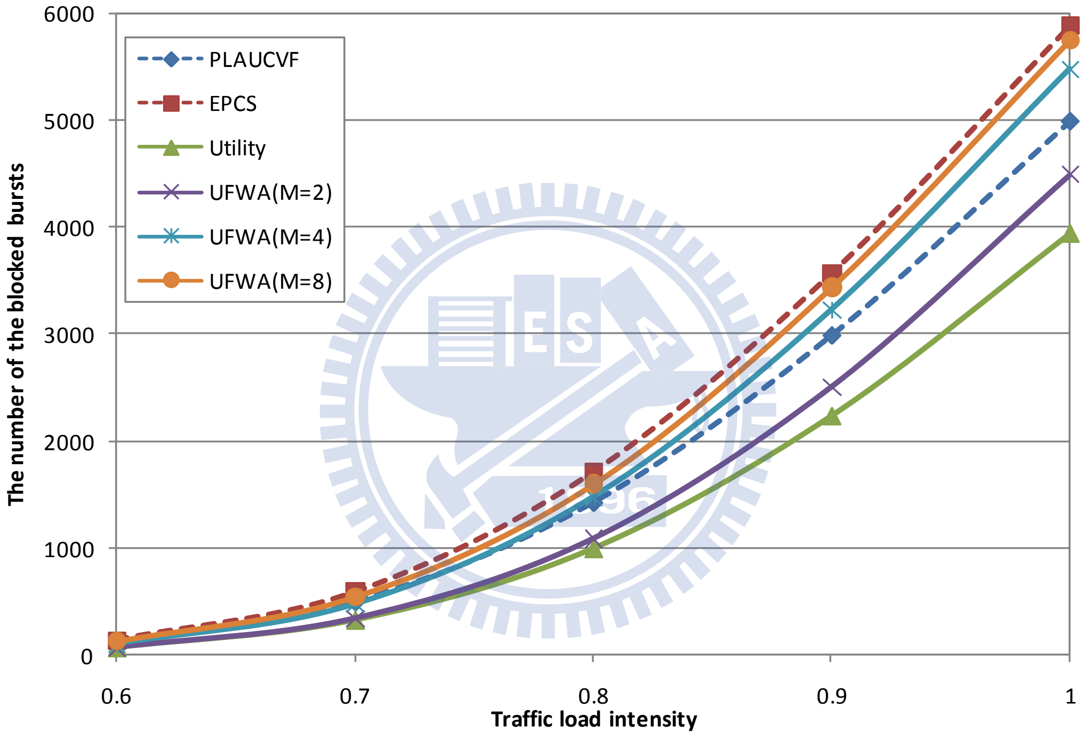

Fig. 4.7 The number of the blocked bursts

4.3.6 Burst loss probability (BLP)

Fig. 4.8 shows the burst loss probability versus the traffic load intensity. The BLP is calculated by the number of the non-preempted bursts plus the number of the non-blocked bursts over the total number of the bursts. It can be found that the proposed UFWA has higher BLP than the other two wavelength assignments. It is because the UFWA considers preempted lengths and preempts shorter length, so that wavelengths do not have too much available duration to accept bandwidth request. In addition, the UFWA attends to preempt larger number due to tight arrangement by considering the other three parameters. But we should notice that even the higher BLP, the UFWA still have higher throughput.

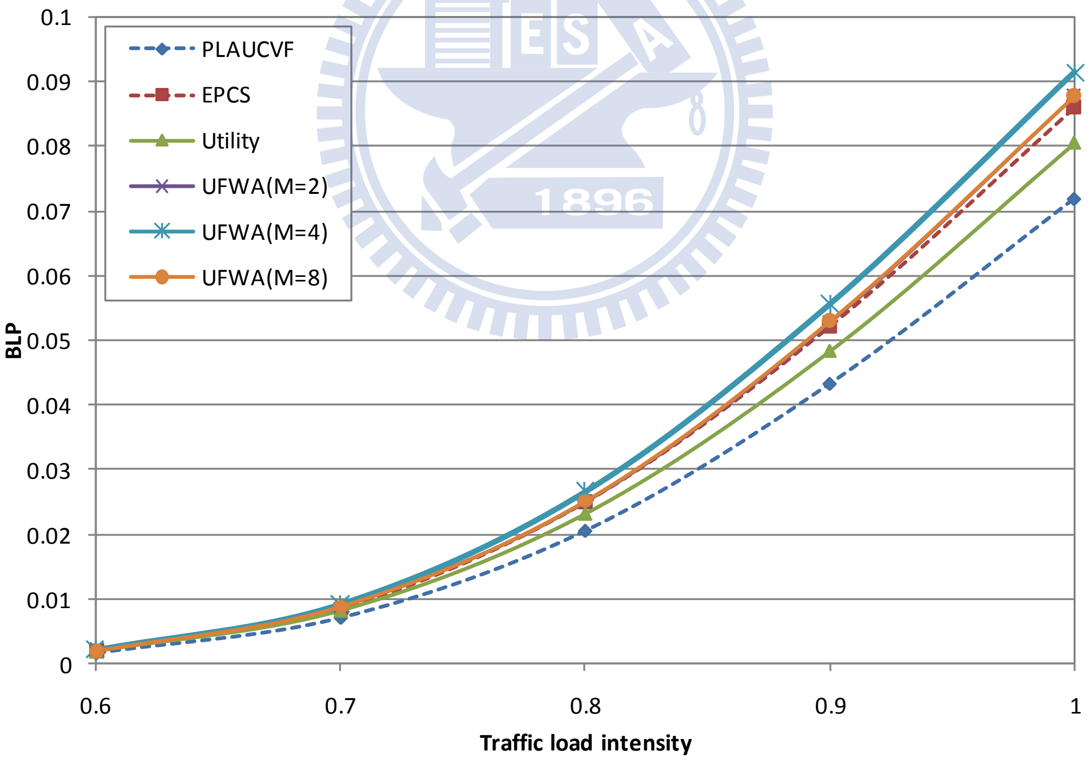

Fig. 4.8 BLP

4.3.7 BLP of the real time traffic

Fig. 4.9 shows the BLP of the real time traffic versus the traffic load intensity. Compared to the total BLP, it can be proved that these three wavelength assignments can support QoS, where the real time traffic has much lower BLP than the non real tine traffic. Although they all have low BLP for the real time traffic, the EPCS has relatively higher BLP than the others. The reason of having higher BLP is that the EPCS uses the shared region to protect the non real time traffic not to be preempted. Obviously, the shared region can help improve the throughput due to longer non real time bursts but it does lead to higher BLP of the real time traffic.

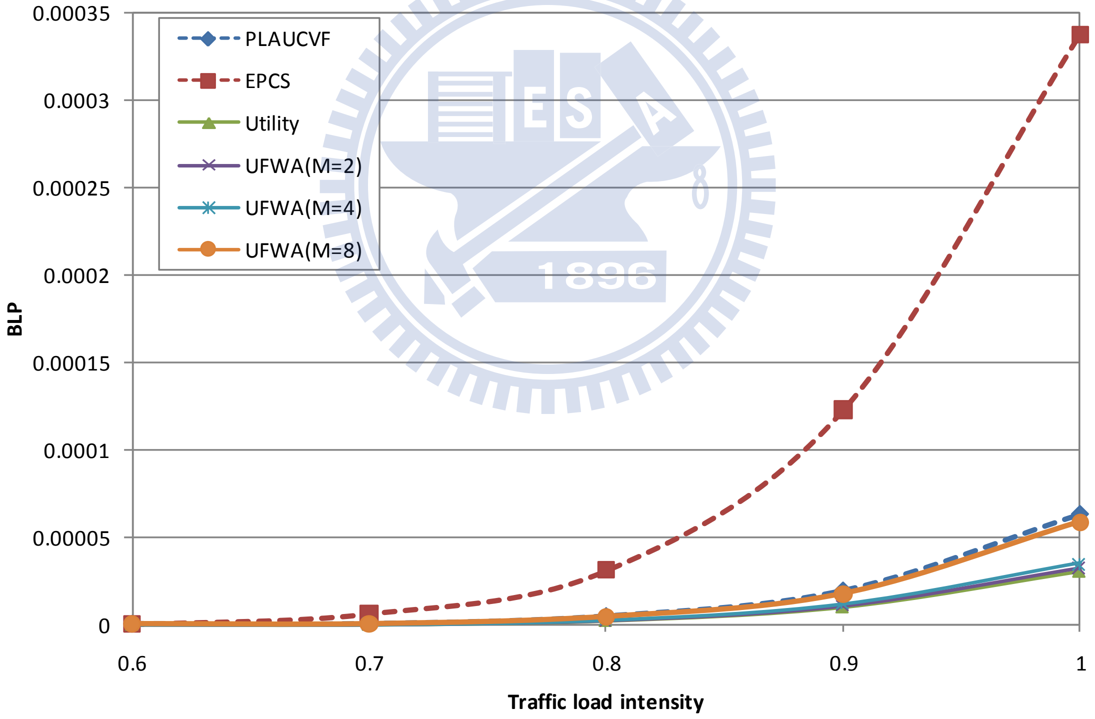

Fig. 4.9 BLP of the real time traffic

4.3.8 Average delay of the real time traffic

Fig. 4.10 illustrates the average delay of the real time traffic versus the traffic load intensity. It can be found the delay is getting larger while the traffic load intensity is getting stronger. It is because the more bandwidth requests, the requesting duration will have more chance to be overlapped, so that we would use FDLs to delay the DBs to find some available duration more frequently. The more frequently we use FDLs, the shorter ones could be not available any more, longer FDLs then would be used. Besides, the UFWA make a balance between the used lengths of FDLs and the voids, so that the UFWA would use longer FDLs to have smaller voids to make wavelengths arranged more tightly. That is why the UFWA would use longer delay than the others. Although the UFWA uses longer delay, we should realize that the usage of FDLs is based on a basic delay time *D*. So even the longer FDL the UFWA uses, it is just a basic delay time larger than the others.

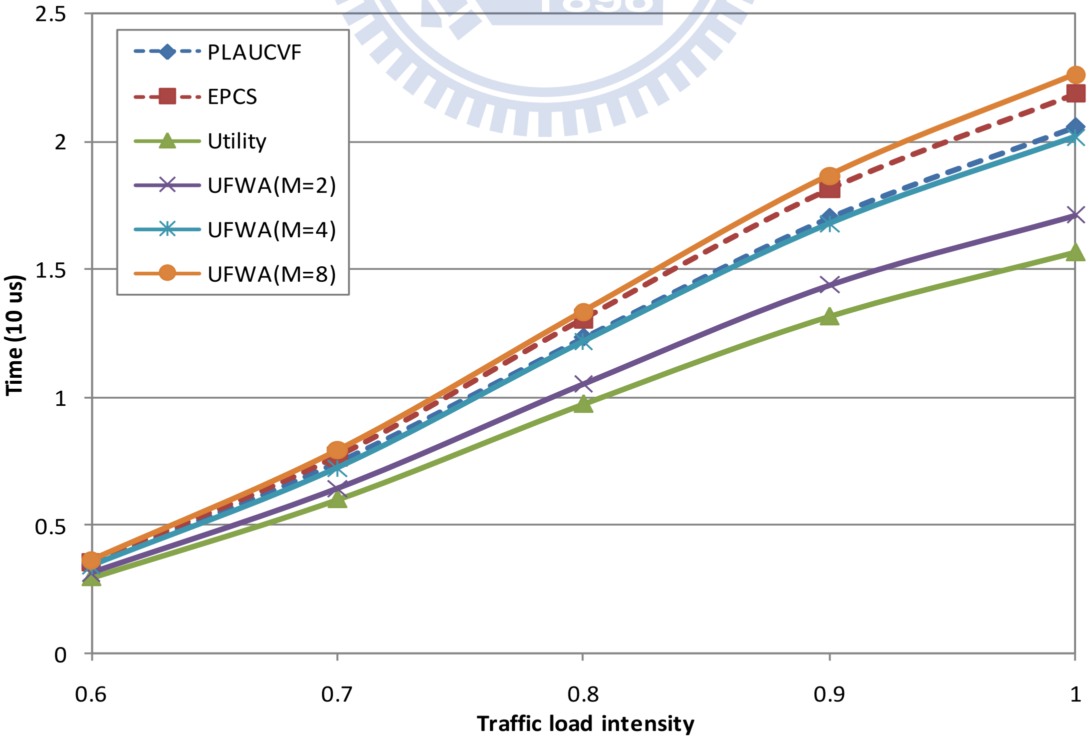

Fig. 4.10 Average delay of the real time traffic

4.3.9 Limited Preemption UFWA

To observe the simulation result of the BLP of the real time traffic, we can find that BLP of the real time traffic is too low. Considering the nature of the shorter burst length of the real time traffic, we proposed a limited preemption scheme to modify the proposed UFWA to try to improve the throughput, called limited preemption UFWA (LP-UFWA). While doing wavelength pre-assignment function on the w^{th} wavelength and the preemption index (R_w) exceeds a threshold, P_{th}, we would set R_w equal to -1 not the original value, where -1 means the associated DB is blocked on the w_{th} wavelength. The following two figures, fig.4.11 and fig. 4.12 will show the improvement of the throughput and the associated BLP of the real time traffic. And the simulation results will be based on a threshold, P_{th}, which is equal to 1.5, equivalent to 15 time longer preempted length than the real time traffic. It can be found that the limited preemption does improve the throughput about 150 Mbps at traffic load intensity equal to 1. Especially for the utility method and the UFWA (M=2), the limited preemption scheme limit the occurrences of preemption, and that would overcome the weakness of preempting too much characteristic of the two algorithms. Fig. 4.12 shows the BLP of the real time traffic versus the traffic load intensity. Even the BLP is increasing dramatically compared to the original proposed UFWA, it is still only about 0.2% when the traffic load intensity equal to 1. Therefore, the LP-UFWA can maintain BLP of the real time traffic at a low level but improve the throughput.

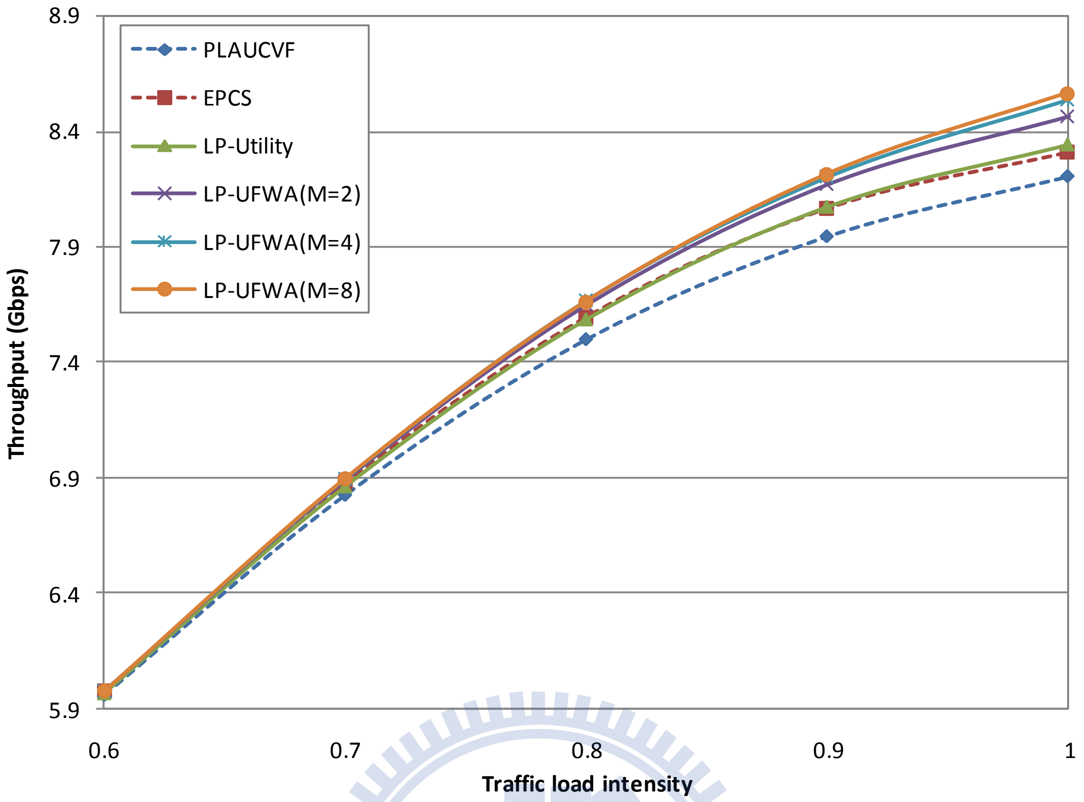

Fig. 4.11 Throughput of the Limited Preemption UFWA (LP-UFWA)

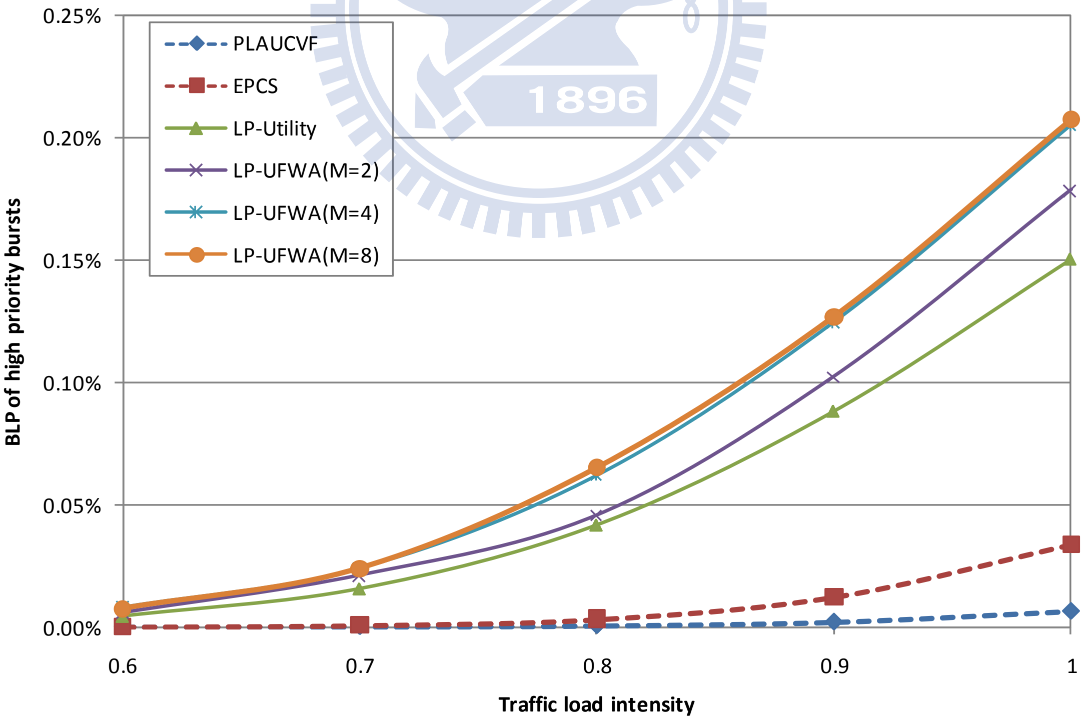

Fig. 4.12 The BLP of the real time traffic of the LP-UFWA

Chapter 5
Conclusions

The paper proposed the utility-based fuzzy wavelength assignment (UFWA) to not only support QoS, but also achieves higher throughput. The UFWA uses the suitable wavelength concentrator (SWC) to reduce the number of the placements of the fuzzy wavelength evaluator (FWE). The SWC also does the wavelength pre-assignment function on all W wavelengths, so that we can let all wavelengths to find their own scheduled ways other than the PLAUCVF and the EPCS. In addition, the UFWA uses four parameters, including preemption index, the used length of the FDL, void, and utilization to describe the wavelength pre-assignment results on all wavelengths. By considering these four parameters, the UFWA can use the utility function and the fuzzy logic system to make a balance between the used lengths of FDLs and the voids, and preempt bursts as short as possible. The fuzzy logic system can help us to classify these four parameters into several linguistic variables using associated fuzzy membership functions. Then we can utilize fuzzy rules to evaluate each wavelength's adequate degree. To observe the simulation results, we find when M=4, the UFWA achieves almost the same high throughput as M=8 but we only have to place half of the number of the FWEs than the UFWA when M=8. Besides, M=4 has shorter delay due to the more serious protection of using FDLs by the utility function.

Moreover, due to the relatively low BLP of the real time traffic and the nature of delay sensitive of the real time traffic (shorter burst length), we proposed another algorithm, called the limited preemption UFWA (LP-UFWA) to achieve the higher throughput but still keep the low BLP of the real time traffic about 0.2% even when traffic load intensity equal to 1.

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Vita

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