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**Absolute Quality-of-Service Differentiation in Optical Burst Switching Networks**

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# **Absolute Quality-of-Service Differentiation in Optical Burst Switching Networks**

By

**Hongbo Lui**

A thesis submitted to

The Faculty of Graduate and Postdoctoral Studies

In partial fulfillment of the requirements

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# Abstract

Absolute Quality of Service (QoS) differentiation is an important issue in Optical Burst Switching (OBS) networks. This thesis aims at providing loss rate guarantees for the priority-guaranteed (PG) classes on an end-to-end (E2E) basis while keeping the loss rate of the best effort (BE) class traffic as low as possible.

We first present a per-hop absolute QoS differentiation scheme called Reserve-and-Preempt Scheme (RPS). The Analytical model of RPS is provided as well. In order to support networks with multiple PG classes, RPS is extended into a variety of new schemes. Among the proposed schemes, Extended Reserve-and-Preempt Scheme (ERPS) is easier to implement and provides the best performance.

On an E2E basis, we apply ERPS over an entire OBS network. To achieve a balance between scalability and unnecessary bandwidth consumption on the intermediate links, we propose optimized priority grouping with single-class constraint (OPT-SC) and optimized priority grouping without single-class constraint (OPT-NC). Furthermore, to cope with the

traffic-fluctuation and the load-unbalance problems in OBS networks, we present a novel self-adaptive algorithm, which integrates two priority-level adjustment mechanisms, priority-level upgrading (PLU) and priority-level degrading (PLD).

Extensive simulations are conducted to demonstrate the effectiveness of the proposed schemes. Simulation results show that our proposed RPS scheme outperforms the existing schemes. The correctness of the analytical model of RPS is demonstrated by simulation. We also observe that ERPS performs the best among the schemes extended from RPS. Simulation results also demonstrate that the proposed OPG-SC and OPG-NC techniques can reduce the bandwidth consumed by the PG classes and improve the performance of the BE class. Finally, we observe that the proposed self-adaptive algorithm can improve the performance of the PG classes with minimum expense on the BE class. At the same time, it is shown to be self-adaptive to traffic fluctuation.

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# List of Acronyms

<b>BE</b>	Best-effort class
<b>BED</b>	BE Class Burst Dropping Approach
<b>BEP</b>	BE Class Burst Preempting Approach
<b>BHP</b>	Burst Header Packet
<b>BORA</b>	Burst Overlap Reduction Algorithm
<b>DVLP</b>	Dynamic virtual lambda partitioning Scheme
<b>DWG</b>	Dynamic Wavelength Grouping
<b>E2E</b>	End-to-End
<b>EDWG</b>	Extended Dynamic Wavelength Grouping
<b>ERPS</b>	Extended Reserve-and-Preempt Scheme
<b>ESWG</b>	Extended Static Wavelength Grouping
<b>FDL</b>	Fiber Delay Line
<b>FPB</b>	Flow-priority-bundle
<b>FPG</b>	Fixed Priority Grouping
<b>IP</b>	Internet Protocol

<b>LAUC</b>	Latest Available Unscheduled Channel algorithm
<b>LAUC-VF</b>	Latest Available Unscheduled Channel with void filling algorithm
<b>min-SV</b>	minimum starting void scheme
<b>min-EV</b>	minimum ending void scheme
<b>OBS</b>	Optical Burst Switching
<b>OCS</b>	Optical Circuit Switching
<b>OPG</b>	Optimized Priority Grouping
<b>OPG-NC</b>	Optimized Priority Grouping without Single-Class Constraint
<b>OPG-SC</b>	Optimized Priority Grouping with Single-Class Constraint
<b>OPS</b>	Optical Packet Switching
<b>PG</b>	Priority-Guaranteed class
<b>PLD</b>	Priority-Level Degrading
<b>PLU</b>	Priority-Level Upgrading
<b>PPS</b>	Probabilistic Preemptive Scheme
<b>PWA</b>	Priority-based Wavelength Assignment algorithm
<b>QoS</b>	Quality-of-Service
<b>RPS</b>	Reserve-and-Preempt Scheme
<b>RPS-DWG</b>	Integrated Scheme of RPS and DWG
<b>RPS-EDWG</b>	Integrated Scheme of RPS and EDWG
<b>RPS-ESWG</b>	Integrated Scheme of RPS and ESWG
<b>RPS-SWG</b>	Integrated Scheme of RPS and SWG
<b>SBP</b>	Scheduled Burst Preemption

<b>SPG</b>	Stopping Over-preempting PG Class Bursts Gradually
<b>SPT</b>	Stopping Over-preempting PG Class Bursts by a Hard Threshold
<b>SWG</b>	Static Wavelength Grouping
<b>VoIP</b>	Voice over IP
<b>WDM</b>	Wavelength Division Multiplexing

# List of Symbols

$C_i$	Class $i$
$D_{C_i}$	Dropped burst number of class $C_i$
$D_{sd}$	Hop-distance of the route between source $s$ and destination $d$
$DTT_i$	Distance-to-Threshold of class $C_i$
$f_{i,sd}$	Flow of class $C_i$ between source node $s$ and destination node $d$
$G_i$	Priority group $i$
$H_{m,n}$	Maximum hop-distance among the paths sharing link $l_{m,n}$
$L_{C_i,h}$	Priority composed of flows of class $C_i$ passing through $h$ hops
$l_{m,n}$	Link between node $m$ and node $n$
$l_{sd}^k$	$k$ th intermediate link along the path between source node $s$ and destination node $d$
$p_{C_i}$	Monitored loss rate of class $C_i$
$\overline{p_{C_i}}$	Loss rate threshold of class $C_i$

$p_{C_i, sd}^k$	Monitored per-hop loss rate of flow $f_{i, sd}$ at the $k$ th intermediate along its path
$p_{C_i, h}^{\max}$	Maximum per-hop loss rate of class $C_i$ flows passing through $h$ hops
$p_{C_i, sd}^{\max}$	Maximum per-hop loss rate of flow $f_{i, sd}$ along its path
$p_{C_i, sd}^{k}$	Expected per-hop loss rate of flow $f_{i, sd}$ on the $k$ th hop along its path
$p_{C_i, sd}^{mn}$	Expected per-hop loss rate of the flow $f_{i, sd}$ on link $l_{m, n}$
$\overline{p_{C_i}}$	Per-hop loss threshold of class $C_i$
$\overline{p_{G_i}}$	Per-hop loss threshold of priority group $C_i$
$\overline{p_{C_i, sd}}$	Per-hop loss threshold of flow $f_{i, sd}$
$\overline{p_{C_i, h}}$	Per-hop loss threshold of priority $L_{C_i, h}$
$P_{C_i, sd}^{e2e}$	Expected E2E loss rate of the flow $f_{i, sd}$
$P_{C_i, sd}^{e2e}$	Monitored E2E loss rate of flow $f_{i, sd}$
$\overline{P_{C_i}^{e2e}}$	E2E loss threshold of class $C_i$
$R_{C_i}$	Scheduled-burst-preemption (SBP) probability of class $C_i$
$w$	Total number of wavelengths
$w_i^A$	Allocated number of wavelengths of class $C_i$
$w_i^O$	Number of occupied wavelengths of class $C_i$
$w_i^R$	Requested number of wavelengths of class $C_i$
$\lambda_{C_i}^{sd}$	Arrival rate of class $C_i$ traffic between source node $s$ and destination node $d$

$\lambda_{C_i,h}$	Arrival rate of priority $L_{C_i,h}$
$\lambda_{sd}$	Arrival rate between source node $s$ and destination node $d$
$\lambda_i$	Arrival rate of class $C_i$ bursts
$\varepsilon$	Load-increase safety constant
$\delta$	Guard space
$\mu$	Transmission rate on a wavelength
$\nu$	The rate on which BE bursts preempt PG bursts when there are no idle wavelengths available
$\Delta$	Degrade safety constant

# Chapter 1

## Introduction

### 1.1 Background

Nowadays, our demands for network bandwidth are increasing daily. To meet our ever-increasing needs for network bandwidth, wavelength-division multiplexing (WDM) technology emerged as a core transmission technology for the next-generation IP backbone network with its ability to provide enormous bandwidth at the physical layer.

Some optical switching paradigms have been proposed to utilize the raw bandwidth available at the WDM layer. Among these paradigms are optical circuit switching (OCS), optical packet switching (OPS), and optical burst switching (OBS). In OCS, data are transmitted after a circuit is established using a dedicated wavelength. Its drawback, however, is its inflexibility to cope with traffic-fluctuation and changing link state. In OPS, data are

transferred in packets. Every core node needs optical buffers or fiber-delay-lines (FDLs) to hold every arriving packet until its header is processed and the switch is properly configured. However, the immaturity of optical memory and optical logic technologies restricts the implementation of OPS in optical networks.

In OBS, data are transferred in bursts, each of which is a group of packets assembled together at an ingress node. Every burst has a burst-header-packet (BHP), which is sent on a separate wavelength before the burst is transmitted. On every intermediate node along its path, the BHP of the burst will have been processed and the switch will have been properly setup before the burst arrival. As a result, optical buffers or FDLs are not necessary and the burst can be transmitted to its destination all-optically. Moreover, the bursts are scheduled on wavelengths statistically. Therefore, OBS does not need to setup a circuit before data are transmitted and is more flexible to handle traffic-fluctuation and changing link state.

OBS has been accepted as a promising optical switching paradigm that combines the advantages of OCS and OPS while circumventing their drawbacks.

## **1.2 Motivation**

Currently, while bandwidth requirement in networks increases exponentially, the Internet is gradually becoming a mission-critical platform for conducting business. Through the Internet, people send email, watch movies, chat online etc., and different applications require different Quality-of-Service (QoS) guarantees.

In OBS networks, the bandwidth is reserved in a one-way mode, which aggravates the contention problem. Furthermore, in OBS networks, the core nodes have very limited buffering capabilities, and the bursts are switched through the core nodes in a cut-through mode rather than a store-and-forward mode. Thus, when a contention between two bursts cannot be resolved, one of them will have to be dropped. Therefore, burst loss is one of the major issues in OBS networks. The high loss rate in OBS networks makes QoS differentiation more important. As a result, we need mechanisms to differentiate between bursts with different service requirements and provide QoS guarantees in OBS networks.

QoS differentiation can be implemented by relative QoS model or absolute QoS model. In the relative model, the QoS performance of a class is defined relatively in comparison to other classes. In other words, the relative QoS model can guarantee that a higher priority class experiences a better service than a lower priority class. However, the relative QoS model cannot guarantee that a class experiences performance that is better, or at least not worse, than a preset threshold. Many mission-critical applications, such as voice-over-IP (VoIP) and IP-TV, need a worst-case QoS guarantee, since they often require fixed bit rates and may be delay sensitive. In order to support the mission-critical Internet traffic, networks need to support absolute QoS model, which defines the performance of each service class quantitatively in absolute terms.

In general, the factors affecting the quality of real-time services include delay and packet loss rate. In this thesis, we focus on core nodes instead of edge nodes and assume that there are no buffers available at the core nodes. Every burst passes through the core nodes along its

path from ingress node to egress node “transparently”, and the delay is induced only by the propagation delay in the optical domain. Therefore, we do not consider delay here and this thesis focuses on absolute loss differentiation among different service classes.

Several absolute QoS schemes have been proposed in OBS networks to guarantee that the Priority-Guaranteed (PG) classes experience End-to-End (E2E) loss rates lower than their preset thresholds. To meet the absolute QoS requirements of the PG classes, the Best-Effort (BE) class traffic suffers from a performance penalty. Obviously, besides satisfying the QoS requirements of the PG classes, the other important concern in an absolute QoS model should be how to minimize the performance penalty suffered by the BE class and improve its performance. However, most of the existing absolute QoS schemes in OBS networks ignore the performance of the BE class. To the best of our knowledge, the only existing absolute QoS schemes that take the performance of the BE class into consideration is the early-drop-based schemes [ZHA04b], but these schemes do not utilize bandwidth efficiently enough.

## **1.3 Objectives**

To overcome the drawbacks of the existing absolute QoS schemes in OBS networks, we need a new absolute QoS differentiation scheme to support OBS networks. This thesis is committed to providing a solution to make the PG classes meet their respective E2E loss requirements while minimizing the performance penalty from which the BE class suffers.

In particular, our objectives are as follows:

- On a per-hop basis, to propose a QoS differentiation scheme which provides as much bandwidth as possible for the BE class traffic while guaranteeing the loss requirements of the PG classes.
- On an E2E basis, to apply the proposed per-hop QoS differentiation scheme to an entire OBS network. Thus, a maximum number of PG flows can be satisfied of their E2E loss requirements while the BE class traffic can experience a minimum loss rate.

## **1.4 Thesis Contributions**

The contributions of this thesis can be summarized as follows:

- On a per-hop basis, a QoS scheme with BE class support, which is called Reserve-and-Preempt Scheme (RPS), is proposed. With this scheme, the loss rates of the PG classes are guaranteed while being kept as close to their thresholds as possible. At the same time, the traffic of the BE class can access the spare bandwidth to the largest extent and the bandwidth is efficiently utilized.
- An analytical model of the RPS scheme is provided based on Markov Chains.
- To support multiple PG classes in OBS networks and further improve the per-hop performance, a variety of schemes, which are based on the RPS scheme, are proposed. The schemes include:
  - Integrated scheme of RPS and Static Wavelength Grouping (RPS-SWG),

- Integrated scheme of RPS and Dynamic Wavelength Grouping (RPS-DWG),
  - Integrated scheme of RPS and Extended Static Wavelength Grouping (RPS-ESWG),
  - Integrated scheme of RPS and Extended Dynamic Wavelength Grouping (RPS-EDWG),
  - Extended RPS scheme (ERPS).
- Based on the proposed ERPS scheme, an E2E absolute QoS architecture is proposed. In this architecture, a burst could be assigned to different priority-groups at different intermediate nodes along its path from the source to the destination. Along its path, the burst is attached with different labels that identify its priority-groups at the intermediate nodes. The proposed ERPS scheme is applied at each intermediate node based on the priority-groups the bursts belonging to.
  - Two optimized priority grouping (OPG) techniques, Optimized Priority Grouping with Single-Class Constraint (OPG-SC) and Optimal Priority Grouping without Single-Class Constraint (OPG-NC), are presented. The OPG techniques can make the PG flows release the bandwidth that is not necessary to satisfy their E2E loss requirements and thus reduce the unnecessary bandwidth consumption. As a result, the BE class traffic can get a higher chance to have its bursts delivered.
  - Two self-adaptive mechanisms, Priority-Level Upgrading (PLU) and Priority-Level

Degrading (PLD), are provided to solve the load-unbalance and the traffic-fluctuation problems. With PLU, more PG flows can be satisfied with their E2E loss requirements. On the contrary, with PLD, bandwidth can be released by higher-priority flows and accessed by the BE class traffic, and thus the performance of the BE class traffic can be improved. Finally, PLU and PLD are integrated into a self-adaptive algorithm, which can improve system performance further.

- Extensive simulations are conducted to compare the performance of the proposed schemes and demonstrate the effectiveness of the proposed schemes and algorithms.

## **1.5 Thesis Outline**

The thesis is organized as follows. Chapter 2 provides an overview of the OBS backbone network architecture. Scheduling algorithms and contention resolution schemes are presented as well. In particular, existing QoS differentiation schemes, both in relative QoS category and in absolute QoS category, are introduced. Chapter 3 presents the proposed RPS scheme on a per-hop basis. The analytical model of the RPS scheme is developed in this chapter. To further improve the performance, a variety of schemes, which are extended from the RPS scheme, are also presented. Chapter 4 is dedicated to providing absolute QoS differentiation on an E2E basis. To provide an absolute E2E QoS differentiation over an entire network, we need to apply the proposed ERPS scheme on every link. Hence, a per-hop loss threshold needs to be set on every intermediate link in order to guarantee the loss requirement for each flow. In order to achieve a balance between scalability and unnecessary bandwidth

consumption problems, two optimized priority-grouping techniques, OPG-SC and OPG-NC, are presented. In addition, to cope with the traffic-fluctuation and the load-unbalance problems, we propose the Priority-Level Upgrading (PLU) and the Priority-Level Degrading (PLD) mechanisms in this chapter. Finally, PLU and PLD are integrated into an integrated self-adaptive algorithm to provide better performance. In Chapter 5, we present simulation models, numerical results and performance analysis. Chapter 6 concludes this study and provides research intents in the future.

## **Chapter 2**

# **Background and Literature Survey**

## **2.1 Introduction**

In this chapter, we provide background information on OBS networks in order to facilitate the discussions in the following chapters. The chapter starts by introducing the background of OBS as a promising optical switching paradigm in the next-generation IP-over-WDM networks. Then different OBS architectures are presented. The scheduling schemes and the contention resolution schemes in OBS networks are briefly explained since they are closely related to QoS differentiation. Finally, we present existing QoS differentiation schemes in OBS networks.

## **2.2 Why OBS?**

Currently, the Internet has become an indispensable part of our daily life. Through Internet,

we send and receive email, play games, watch movies, chat with friends, pay our bills, and this list goes on and on. Therefore, the Internet traffic increases explosively. Up to March 2006, the number of broadband subscribers increased by over 119% compared to the previous year and achieved 23 million in Japan [JAP06]. In the US, Internet Protocol (IP) traffic grows by approximately 100% each year at the backbone network [ODL03]. The explosive growth in IP traffic drives the demands for network bandwidth.

To meet our ever-increasing needs for network bandwidth, wavelength-division multiplexing (WDM) technology [BRA90] [NEW97] [VAR97] [VIS98] [MAN98] emerged as a core transmission technology for the next-generation IP-over-WDM network [GHA00]. The WDM technology builds optical networks by interconnecting various optical switches with WDM fibers. With its ability to support a number of high-speed (gigabit) channels in a single fiber, the WDM technology provides enormous bandwidth at the physical layer, and in the near future, it will be possible to provide hundreds of wavelengths of several Gigabits each. Therefore, framework and protocols at higher layers are needed to utilize the raw bandwidth available at the optical (WDM) layer efficiently.

To meet this demand, some optical switching paradigms for IP-over-WDM have been proposed. Among these paradigms are optical circuit switching (OCS), optical packet switching (OPS), and optical burst switching (OBS).

In OCS, bandwidth is assigned at wavelength level (Figure 2.1(a)). Before data are transferred, a lightpath needs to be established using a dedicated wavelength from source to destination [ZAN00][XUE05]. Once the lightpath is established, the data are transferred

“transparently”, as shown in Figure 2.1(a). OCS is relatively easy to implement, but it requires a certain amount of time for lightpath establishment and release, which are independent of the connection holding time [DAH06][KAM04]. This lightpath setup delay is equal to at least the round trip propagation time [TUR99]. For long holding time, OCS is efficient from a signaling overhead point of view. However, that case leads to a reduced ability to adapt to traffic dynamics. When the channel holding times are very short, the channel usage will become very poor [COU05]. This is especially true if IP traffic with its bursty behavior [CRO97] is carried on top of such an OCS network or the link state changes from time to time in the network.

OPS [YAO00a][YAO00b][BLU01][BLU03][OMA01][ELS02] tries to circumvent the drawback of OCS. In OPS, data are transferred in packet level. Each packet carries a header, which is processed either optically or electrically after optical-electrical-optical (O-E-O) conversion at every intermediate node (Figure 2.1(b)). While the packet header is processed, the data payload has to wait in the fiber-delay-lines (FDLs) before being forwarded to the next node. OPS is conceptually ideal, but current optical technologies such as optical memory and optical logic are not mature enough to be implemented soon [CHA99][BLU03]. Also, when the traffic load is heavy, the O-E-O conversions and the processing of the headers will be a heavy burden for the core nodes. Therefore, scalability is also a problem in OPS networks.

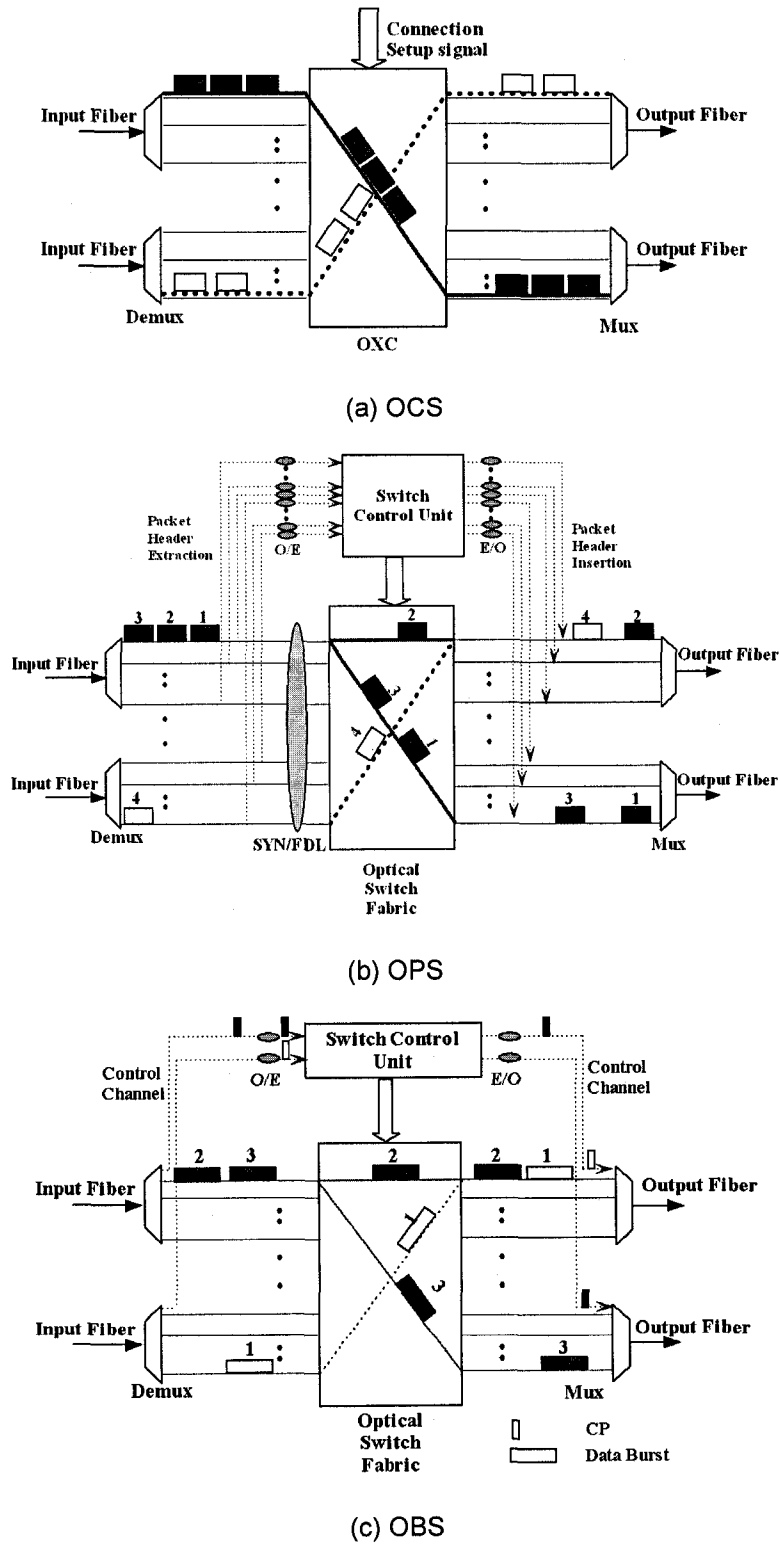


Figure 2.1 Different Switching Node Architectures

In this situation, OBS [YOO97][YOO98][YOO99][QIA99][TUR99][WEI00] [CHE04] emerged as a promising approach that combines the advantages of OCS and OPS while circumvents their drawbacks. In an OBS network, multiple packets from local access networks are assembled at the ingress nodes into bursts, and each burst has a corresponding burst-header-packet (BHP), which is sent on a separate channel (Figure 2.1(c)). On one hand, OBS uses out-of-band signaling to reserve bandwidth. Hence, like OCS, data can be switched through the network “transparently” without optical buffers or even FDLs. On the other hand, similar to OPS, OBS schedules bursts “statistically” at each channel and eliminates the need to setup lightpath before data transmission. Therefore, OBS uses data bandwidth more efficiently (According to [XUE03], under the identical network capacity and traffic demand, OBS can achieve about 20% higher throughput than OCS) while reducing data delay. In addition, OBS is scalable compared to OPS because multiple packets share a “header” (BHP). Table 2-1 compares OCS, OPS and OBS. Because of its advantages over OCS and OPS, OBS has been attracting increasing attention from both academia and industry worldwide.

Table 2.1 Comparison of OCS, OPS and OBS

Optical Switching Paradigms	Bandwidth Utilization	Latency (setup)	Optical Buffer	Processing. Overhead
OCS	Low	High	Not required	Low
OPS	High	Low	Required	High
OBS	High	Low	Not required	Medium

## 2.3 OBS Architecture

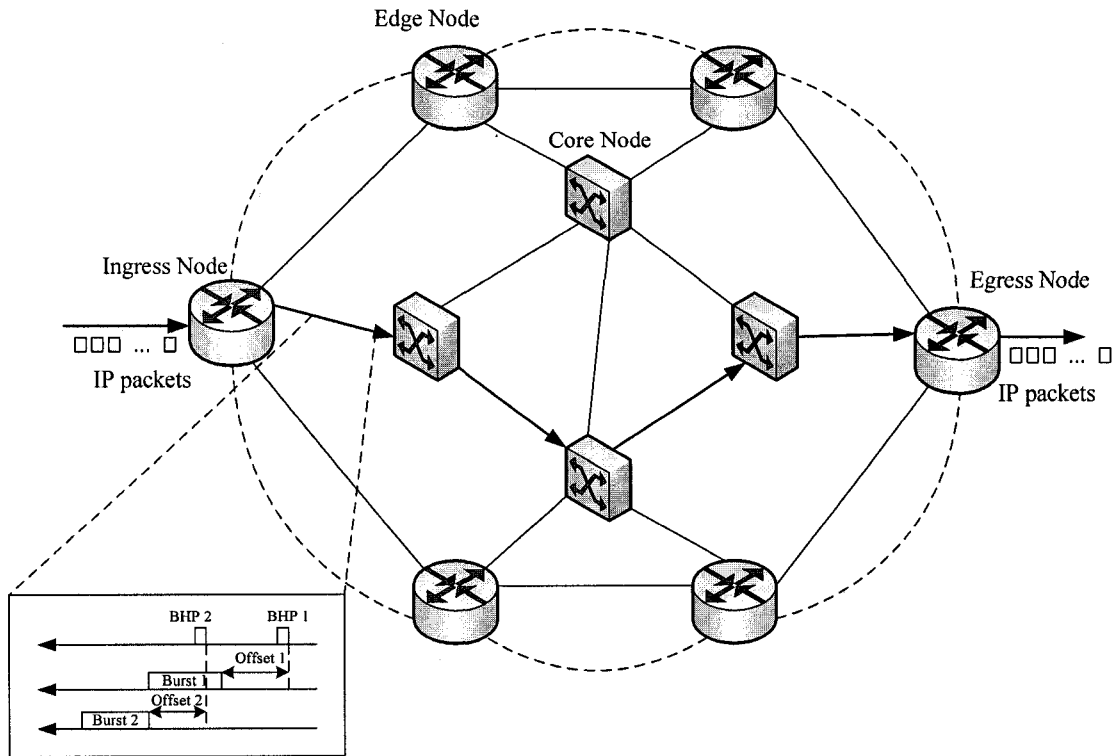


Figure 2.2 OBS Network

The concept of burst switching was introduced for centralized Time-Division Multiple Access (TDMA) systems [MIL90] and Asynchronous Transfer Mode (ATM) networks [WID95] in early 1990s. OBS protocols suitable for high-speed WDM networks were not developed until 1997 [YOO97]. Researchers have proposed a variety of OBS architectures [YOO97][QIA99][TUR99][WEI00]. However, there are some common characteristics among these variants. As shown in Figure 2.2, in an OBS network, multiple packets from local access networks are assembled at ingress nodes into bursts. The most important feature of OBS is that BHPs and payloads are sent separately on different channels or wavelengths.

Before a burst is transmitted, a BHP is sent out on a separate channel and leads the burst by an offset-time. This BHP carries information about the corresponding burst such as burst length and offset-time. Before a burst arrives at an intermediate node along the way, its corresponding BHP will have already arrived and been processed electronically. Then according to the information carried by the BHP, every switch along the path, from the ingress node to the egress node, tries to schedule the burst on the desired wavelength and reserve bandwidth for the incoming burst. The data burst follows the BHP by an offset-time without waiting for the acknowledgement for connection establishment. When the burst arrives at an intermediate node, the bandwidth will have been reserved and the switch will have been configured properly already, thus the burst can be switched to the desired output port without any optical-electrical-optical (O-E-O) conversion or any extra delay [TEN04b]. When the burst arrives at the egress node, it is disassembled into packets, which go to their destinations via local access network.

Many variants of OBS signaling protocols have been proposed, such as just-enough-time (JET) [YOO97], just-in-time (JIT) [WEI00], horizontal scheduling [TUR99], time slotted OBS [RAM03][ZHA06], hybrid system of OCS and OBS [LEE03a], adaptive reliable OBS [YU05a], synchronous stream OBS [YU05b] and wavelength routed OBS [DUS00][MIG01][KOZ01][DUS02]. Among them, the most representative ones are JET and JIT.

### 2.3.1 Just-in-Time (JIT)

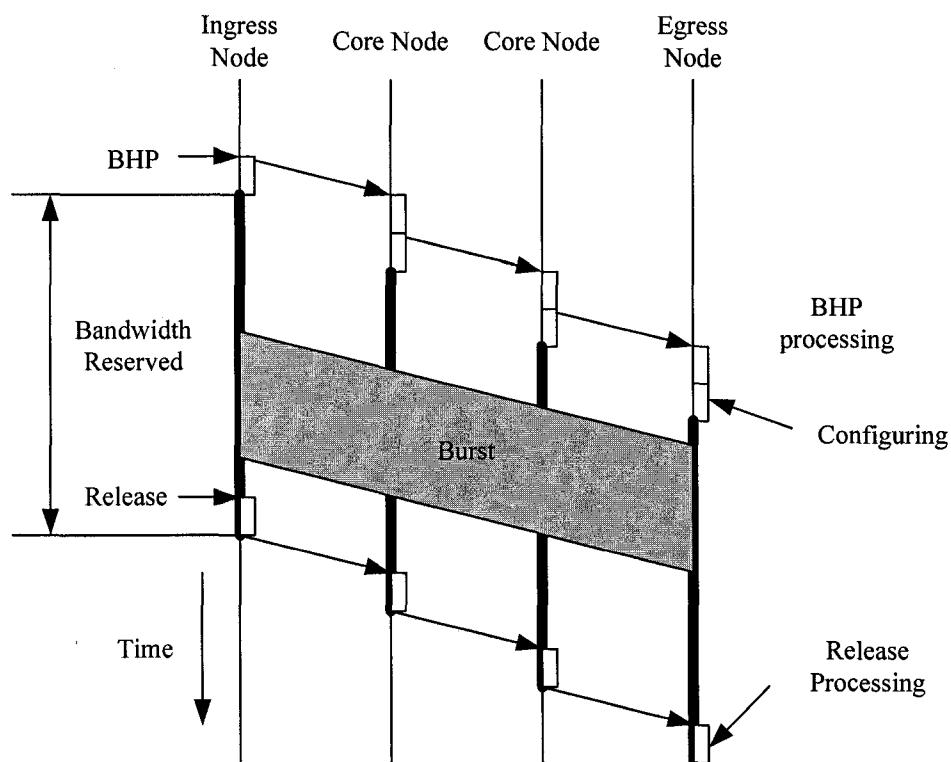


Figure 2.3 Just-in-Time

The operation of JIT [WEI00][BAL02][MAR06] is shown in Figure 2.3. Once the BHP is processed at an intermediate switch, the switch is configured and a wavelength is immediately reserved for the incoming burst. After the burst has been transferred completely, the source node sends a release packet along the path to release the bandwidth at each node. From Figure 2.3, we can see that before a data burst is transferred, a wavelength has been reserved for it and cannot carry any traffic at any intermediate node [KIR06]. Hence, the JIT scheme results in bandwidth inefficiency.

### 2.3.2 Just-Enough-Time (JET)

JET [QIA99] is illustrated in Figure 2.4. In JET, the transfer time for each burst at every intermediate node is well planned. At each intermediate node, the bandwidth is reserved for an incoming burst just before the burst arrives at the node, and released immediately after the transfer is complete. Therefore, at each intermediate node, the bandwidth is reserved for the incoming burst only for the duration of the burst. The void (time interval) before the arrival of the burst at the intermediate node can be used to schedule some other bursts. Compared to JIT, JET uses the bandwidth more efficiently.

In this thesis, we use JET as the signaling scheme in OBS networks.

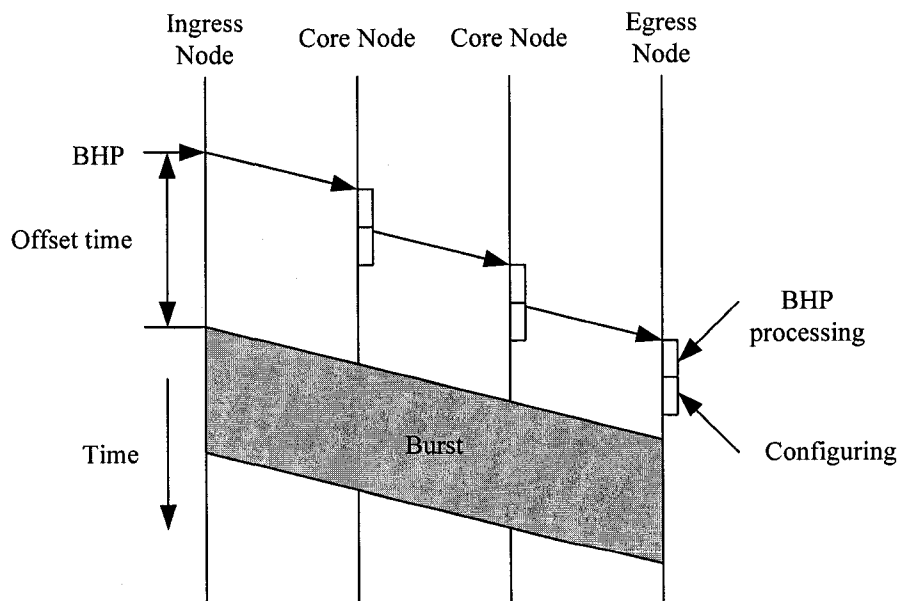


Figure 2.4 Just-Enough-Time

## 2.4 Scheduling Schemes in OBS networks

When wavelength converters are available at a core node in an OBS network, an incoming burst can have multiple wavelengths to choose. According to the scheduling scheme in the network, it may choose a wavelength on its desired output link and reserve bandwidth on the wavelength.

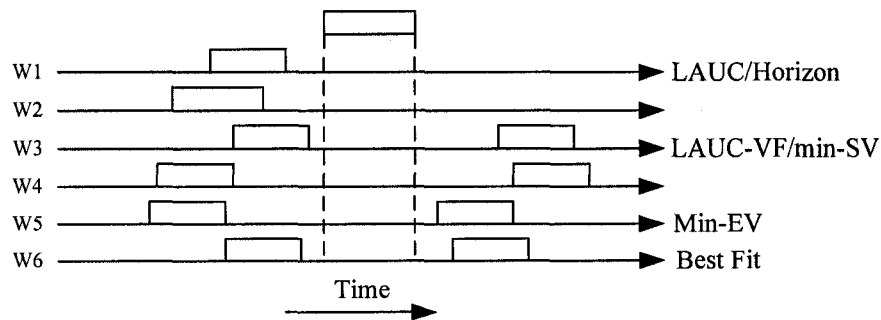


Figure 2.5 Scheduling Schemes

*Latest Available Unscheduled Channel algorithm* (LAUC) [XIO00], also called *Horizontal Scheduling* in [TUR99], is a scheduling scheme that is easy to implement in OBS networks. In this scheme, the only information a core node needs to keep for each wavelength is the scheduling horizon, which is defined as the latest time at which the wavelength is currently scheduled to be in use. When a burst is coming, only the wavelengths whose scheduling horizons precede the burst's arrival time are considered available, and the one whose scheduling horizon is the latest is chosen to schedule the burst. The idea behind this scheme is to minimize the gap between the scheduling horizon and the new burst on the wavelengths. The advantage of the LAUC scheme is its simplicity in implementation. However, in this scheme, the bandwidth cannot be used efficiently, since the gaps between

the scheduled bursts cannot be utilized. In Figure 2.5, because the core node keeps only the end time of the latest burst on the wavelength, only W1 and W2 are available wavelengths. Comparing W1 with W2, we can observe that the scheduling horizon of W1 is later than that of W2. Therefore, the arriving burst is scheduled on W1.

To overcome the drawback of the LAUC scheme, Xiong [XIO00] proposed a scheme called *Latest Available Unscheduled Channel Algorithm with Void Filling* (LAUC-VF). In this scheme, a core node needs to keep both the start time and the end time of every gap on every wavelength. Bursts can be filled in the gaps between scheduled bursts. As a result, the bandwidth utilization improves and the burst loss rate is reduced. As shown in Figure 2.5, the arriving burst is scheduled in W3 with the LAUC-VF algorithm.

In [XU03], the authors proposed several variants of the LAUC-VF algorithm, including min-SV (minimum starting void), min-EV (minimum ending void) and Best Fit. Respectively, min-SV and min-EV try to minimize the starting and the ending voids that are generated between the new burst and a scheduled burst. The min-SV algorithm is functionally the same as the LAUC-VF and its performance is comparable to that of LAUC-VF, but its implementation is faster than that of the LAUC-VF, because it uses a balanced binary search tree as its data structure [XU04]. The Best Fit, on the other hand, tries to achieve a minimum total length of the starting void and the ending void generated after the arriving burst is scheduled. Figure 2.5 shows the scheduling outcome with the different algorithms. Among the three variants, min-SV is the most desirable according to [CHE04].

To avoid possible burst contention at downstream nodes, Wang et al.

[WAN02b][WAN03a] proposed a Priority-based Wavelength Assignment (PWA) algorithm for the ingress nodes in an OBS network. In PWA, each ingress node maintains a wavelength priority list for every destination. When a burst arrives at the ingress node, it checks the wavelength priority list of the destination that the burst is heading for. If the highest priority wavelength is available, the burst is scheduled on the wavelength; otherwise, the wavelength with the second highest priority is checked. The priority of each wavelength is updated dynamically according to its burst loss profile. Simulation results show PWA can reduce loss rate in an OBS network.

In [LI03], the authors proposed several scheduling algorithms that are collectively called as Burst Overlap Reduction Algorithm (BORA). BORA aims at actively avoiding burst contentions that likely occur at downstream nodes through reducing the overlapping degrees at edge nodes. Here, the term “overlapping degree” means the number of bursts that arrives at one link simultaneously. The idea behind this is to serialize the bursts on an outgoing link to reduce the number of bursts that may arrive at downstream nodes simultaneously. As a result, the burst contention and the burst loss rate are reduced at downstream nodes.

## **2.5 Contention Resolution in OBS networks**

This thesis focuses on providing absolute QoS differentiation in OBS networks, and aims to keep the loss rate of each PG class below its threshold. In a QoS-supported OBS network, every core node is equipped with a contention control mechanism to maintain the loss rates of the classes on a per-hop basis. Thus, contention resolution is closely related to QoS

differentiation in OBS networks. Therefore, we introduce contention resolution schemes first.

In OBS networks, contention occurs when two or more bursts compete for the same wavelength on the same output link of a core node. OBS networks use one-way reservation protocols, and the ingress nodes send out bursts without receiving reservation acknowledgements or global coordination. Hence the bursts in OBS networks have more chances to contend with each other. Moreover, in OBS networks, contentions cannot be resolved by electronic buffers since they cannot keep up with the speed of optical networks [XU01]. The bufferless fact makes the situation worse. Therefore, the core nodes need to have the ability to resolve contentions among bursts.

Conventionally, the primary contention resolution approaches are wavelength conversion, deflection routing and FDL delay.

Wavelength conversion is the ability to convert an optical signal on a given input wavelength to some other output wavelength [RAM98][ELM00]. It can dynamically improve the utilization of resources in an optical network, especially in highly dynamic traffic environments such as OPS and OBS. For this reason, wavelength conversion is used as an efficient mechanism to resolve contentions in OBS networks. At a core node with wavelength conversion capability, contentions can be resolved by converting the input wavelength of the contending burst to a different wavelength that is available on the designated output link [DUS02]. The drawback of this approach is that all-optical wavelength converters are still undergoing research and development [ZAN04], and hence are relatively immature and expensive [ROS06]. Therefore, researchers are working on minimizing wavelength

contentions at the core nodes of OBS networks with sparsely deployed wavelength converters [PED06][MAR06][TRI00]. Also, many wavelength assignment schemes in networks without or with sparsely deployment of wavelength converters have been proposed, such as proactive wavelength assignment [LI03], first-fit-random, first-fit-TE [TEN04a] and priority-based wavelength assignment algorithm [WAN02b][WAN03].

In an OBS network, there could be multiple routes between every source-destination pair, and a burst can go through different routes from its source to its destination. Suppose two bursts are contending for the same wavelength on the same output link at a core node where there are no wavelength converters or free wavelengths available. One of the bursts can be routed to its desired output port (primary route) while the other one can be deflected to an available alternate output port and follow a secondary route to the destination [QIA00]. Many deflection routing schemes have been proposed for OBS networks [HSU02] [WAN00] [LEE03b][LEE05b][ZAL04a][OGI05][NGO06]. The advantage of the deflection routing is that it does not need any extra hardware, such as wavelength converters and FDLs. The drawback is that the deflected bursts may end up following a longer path to the destination, leading to higher E2E delay, and bursts may also arrive out-of-order at the destination [VOK03a][NGO06]. As shown in [WAN00], applying deflection routing in an OBS network can reduce the data loss rate and the average delay compared to burst retransmission from source node. However, unlimited deflection in an unslotted system such as an OBE network also deteriorates the performance of the network when the traffic load is heavy [BOR93][BOR94][WAN00]. To address this problem, a Proportional Deflection scheme was proposed for OBS networks in [CHE03].

The lack of an efficient way to store information in the optical domain aggravates contention in OBS networks. Research has focused on ways of emulating electronic buffer capacities through the use of FDLs to delay optical signals [CHL96][HUN98a][HUN98b][TAN00]. An FDL is a fiber of fixed length, and can hold an optical signal for an amount of time determined by the speed of light and the length of the FDL [LU04]. Hence, unlike electronic buffers, FDLs cannot store bursts indefinitely. At a node with FDLs, one of the contending bursts can be delayed for some time after being made pass through an FDL while the other one is passing through the output link they are contending for. After that, the first burst can try to reserve the desired wavelength on the output link again [QIA00][YOO00a][YOO00b]. The problem of this approach is that FDLs can provide only limited delay. In addition, this approach induces higher E2E delay and out-of-order problem [DET05]. Furthermore, FDLs can be bulky and expensive. Researchers have proposed some contention resolution schemes with reduced deployment of FDLs in OBS networks [LEE05a].

Sometimes contentions cannot be resolved with the above methods due to the unavailability of wavelength conversion, output ports, or FDLs. In this case, data loss becomes inevitable. Conventionally, there are two options. The first option is a non-preemptive approach in which an arriving burst is dropped in its entirety. Alternatively, the arriving burst can preempt a scheduled burst based on the priority or traffic profile in a preemptive approach. However, neither of the two approaches can use the bandwidth efficiently, because one of the two contending burst is dropped or preempted in its entirety even when only a small portion of the two bursts overlap with each other. To address the

bandwidth utilization inefficiency problem induced by dropping or preempting the entire burst, an approach called “segmentation” was proposed in order to pass as many packets as possible using the fragmented resources [VOK02a] [VOK03a][VOK05][NEU03]. This approach is also called OCBS in [DET02b]. In this approach, each burst is divided into multiple segments, and each segment is composed of some packets. When a burst contends with another burst, only the segments that overlap with the other burst are dropped or preempted, and the remaining segments will be scheduled. This method utilizes bandwidth efficiently compared to dropping or preempting the entire burst.

What we need to point out is that the above contention resolutions can be used jointly. Some integrated contention resolution mechanisms were proposed to improve system performance in terms of burst loss rate. The authors of [VOK03c] integrated the segmentation and the FDL delay approaches and proposed scheduling algorithms referred to as delay-first and segment-first algorithms. In [GRI05], the segmentation and the deflection routing approaches were integrated. Also, the wavelength conversion and the deflection routing approaches were integrated in [ZAL04b].

## **2.6 QoS Differentiation in OBS Networks**

The Internet is a packet-oriented network based on Internet Protocol (IP), a connectionless networking protocol, and has been designed to offer best-effort services, which does not provide any QoS differentiation. However, the increasing development of the Internet is enabling a variety of new applications in recent years. There are many QoS parameters such

as delay, jitter and loss rate. The importance of these parameters depends on the applications. For instance, some applications can tolerate packet losses but cannot tolerate delays and jitters, while others are time-tolerant but require data integrity [TSA00]. Multimedia applications, which include video streaming, VOIP and online gaming, are important applications in today's Internet. These applications often demand seamless real-time data delivery. Also, these applications demand better service quality with low loss rates, low delays and jitters [SUN05]. Obviously, the wide diversity of the service requirements of the applications makes the best-effort service model inadequate. Therefore, the Internet needs to be extended with service differentiation.

In OBS networks, QoS differentiated services may focus on differentiated delay and differentiated loss rate. The delay consists of the assembly delay at the edge node and the propagation delay, which is determined by the physical distance from the ingress node to the egress node in an OBS network [VU05]. Some QoS schemes providing delay differentiation have been proposed in OBS networks, such as FRR in [LIU03]. In this thesis, we ignore delay differentiation and focus on providing loss rate differentiation in OBS networks.

There are many mechanisms to implement connectionless QoS in the literature [ZHA95][VAR97][BRI98][ZIV02]. However, these approaches incur high processing overhead at the intermediate nodes and require buffers for switching. To date, no efficient optical buffer is available. The use of electronic buffers necessitates O-E-O conversions, which must be avoided in an all-optical network where data are kept in the optical domain at all intermediate nodes [XU01]. The other alternative is the use of FDLs [FEN02], which can

provide only very limited delay functionality at the intermediate nodes. Therefore, new QoS differentiation mechanisms are needed at the WDM layer in OBS networks.

As mentioned before, QoS strategies can be categorized as relative QoS and absolute QoS. In the OBS network domain, most of the QoS schemes belong to the relative QoS category.

### **2.6.1 Relative QoS Differentiation Schemes**

In a relative QoS model, the QoS performance of a class is defined relatively to that of the other classes. The performance of a higher priority class is guaranteed to be better or at least not worse than that of lower priority classes. To date, many relative QoS differentiation schemes have been proposed. The relative QoS differentiation schemes can be roughly classified as offset-time-based QoS differentiation, segmentation-based QoS differentiation, preemption-based QoS differentiation, proportional QoS differentiation and hybrid QoS differentiation.

**Offset-time based QoS differentiation:** An offset-time based QoS differentiation scheme was proposed by Yoo and Qiao in [YOO98] [YOO00c] and an analytical model was given by Barakat and Sargent in [BAR04] and [BAR05]. Based on the JET signaling protocol, this scheme gives each burst of the higher priority classes an extra offset-time while the bursts of the lowest priority class get only a basic offset-time. In this way, the bursts with a higher priority can have a better chance to reserve bandwidth successfully than those bursts with a lower priority. This scheme aims to achieve maximum isolation between different priority classes for service differentiation. However, to achieve the best differentiation, the

extra offset-time has to be at least 4 to 5 times larger than the basic offset-time [YOO99b]. Hence, this scheme results in longer delay and larger buffer requirement at edge nodes. Meanwhile, it may over-penalize the low-priority classes. In particular, it is unfair to the long bursts with a low-priority [CHE01]. According to [POP02], for a given offset-time difference, the loss rate differentiation strongly depends on the burst duration distribution. Hence, the control of the differentiation is difficult. Furthermore, in this scheme, the offset-time has two meanings, one is path length, and the other one is priority. However, the intermediate nodes treat them in the same way. Therefore, it results in the so-called near-far problem [YAN03]. Suppose there are two bursts, one of them is of a higher priority and a shorter path, and the other one is of a lower priority and a longer path. The second burst may have a longer offset-time than the first one does. In this case, the lower priority burst gets a better chance to reserve a channel than the higher priority burst does.

**Segmentation-based QoS differentiation:** Segmentation-based QoS schemes were also studied by researchers. Vokkarane et al. [VOK02b][VOK02c][VOK02d][VOK03a] [VOK03b] proposed tail-dropping based scheme in which every burst is divided into segments and each segment is used to accommodate some packets of a specific class. The priorities of the segments descend from head to tail. Whenever contention occurs between two bursts, the tail of one of the contending bursts, which carries packets with lower priority, is dropped. Then, the remaining segments of the burst, which are of higher priorities, are delivered to destination. Similarly, head-dropping QoS scheme was proposed by Wang [WAN03]. In this scheme, segments are put in a burst with priorities in ascending order from head to tail. In case of contention, the head of the burst will be dropped. The problem of the head-dropping

scheme is that segments may arrive at their destinations out-of-order, assuming that the dropped segments will be retransmitted. Both of the two schemes try to drop segments with lower priorities, therefore segments with higher priorities get a better chance to be delivered.

**Preemption-based QoS differentiation:** The basic idea behind the preemptive QoS differentiation schemes is to allow a high-priority arriving burst to preempt a low-priority scheduled burst when there are no idle wavelengths available. Loi proposed a preemptive model in [LOI02]. Because the loss rate is inversely proportional to the number of idle wavelength, different classes are given different numbers of wavelengths. In other words, classes of higher priorities get more resources. Every class is associated with a usage limit ( $p_i$ ), which is defined as a proportion of system resources the class is allowed to use. At the same time, every core node in the system keeps a usage of class ( $\rho_i$ ) for every class, which is defined as the total duration of the scheduled bursts of that class over the total duration of the scheduled bursts of all classes. Class  $C_i$  is said to be *in-profile* if  $\rho_i \leq p_i$ ; otherwise, it is said to be *out-of-profile*. Whenever a core node receives a burst that is in-profile, it can preempt a burst that is out of profile. Thus, each class can be kept under its usage limit. To improve bandwidth utilization, [LIA04] extended Loi's scheme and allow in-profile bursts to "partially" preempt out-of-profile bursts. In other words, the bursts are segmented and the overlapped part of the out-of-profile bursts can be truncated by the in-profile bursts.

**Probabilistic Preemptive Scheme (PPS):** PPS was introduced by Yang et al. in [YAN03]. With this scheme, upon the arrival of a high-priority class BHP, the core node searches for an

idle period on the desired wavelength first. If there are no idle wavelengths available, the burst will try to preempt a lower-priority burst based on a probabilistic parameter  $p$ . If the preemption is not successful, i.e., all corresponding periods have been reserved for higher-priority bursts, the arriving burst will be simply dropped. Clearly, the preemptive probability  $p$  affects the loss rates for different classes. By changing the probabilistic parameter, the scheme can achieve flexible loss rate differentiation in OBS networks. The advantage of this scheme is that it is simple to implement. However, how to set the preemption probability parameters properly is an open problem. In [YAN03], the authors assume that there are only two classes with only one preemptive parameter  $p$ . Suppose there are  $n$  classes in the system, let  $p_{ij}$  denotes the probability that class  $C_i$  preempts class  $C_j$ , then there will be  $n \cdot (n-1)$  probabilistic parameters. Changing any  $p_{ij}$  ( $i=1, j+1, \dots, n$ ) will affect the loss rate of class  $C_j$  bursts. This observation makes this scheme not scalable to be used in multiple class systems.

**Proportional QoS differentiation:** The idea of proportional differentiation was proposed by Dovrolis and Ramanathan [DOV99][DOV00][DOV01][DOV02] to provide service differentiation on delay. It aims to achieve a predefined proportion between two service classes. In [CHE01], Chen et al. introduced an intentional dropping scheme based on the proportional differentiation idea. Let  $p_i(t)$  be a QoS metric such as blocking probability or packet delay over a time period  $t$ , and  $s_i$  be the differentiation factor for class  $C_i$ , the proportional differentiation model is as  $\frac{p_i(t)}{p_j(t)} = \frac{s_i}{s_j}$ . In the intentional dropping scheme, the

loss rate of each class is maintained in a predefined proportion according to its priority. A higher priority class gets a smaller differentiation factor, which means a smaller predefined proportion, than a lower priority class. An arriving burst of class  $i$  will be dropped if the loss rate of class  $C_i$  is violating its predefined proportion (i.e.,  $\frac{p_i(t)}{s_i} < \frac{p_j(t)}{s_j}$ ) regardless of whether there is an idle wavelength available; otherwise, the burst will make reservation on the wavelength. Through intentional dropping, the bursts of the class, whose predefined proportion is violated, are dropped, and more and longer free periods on the wavelengths in the output link are available to admit bursts of the class whose predefined proportion is not violated yet. As a result, those bursts can get higher chance to reserve bandwidth successfully. The intentional dropping scheme can be used to provide well-controlled proportional differentiated loss rate. However, since this scheme intentionally drops bursts in order to provide a proportional burst loss rate, a burst is dropped whenever its predefined proportion is violated, even if there are idle channels available. This can cause excessive dropping, which results in a low bandwidth utilization and high overall loss rate.

**Hybrid QoS differentiation:** Other researchers have proposed some hybrid schemes to provide service differentiation based on loss rate. To improve bandwidth utilization, Cankaya et al. [CAN03] proposed a new scheme that is similar to Chen's intentional dropping scheme. This scheme combines partial preemption with proportional differentiation that is used in Chen's scheme in order to achieve performance improvement in terms of loss rate and bandwidth utilization. In Cankaya's scheme, whenever a contention happens, the proportional service differentiation profile of the arriving burst is checked to determine

whether it needs to be dropped. If the profile agrees to drop the arriving burst, then only the overlapped part of the arriving burst will be dropped; otherwise, the overlapped part of the scheduled burst will be preempted. Obviously, this scheme can reduce the loss rate of each service class and make bandwidth utilization more efficient compared to the intentional dropping scheme [CHE01].

[TAN04] and [TAN06] proposed a Probabilistic Preemptive Burst Segmentation Scheme (PPBS). Instead of providing absolute QoS, the PPBS scheme aims to achieve better performance for higher priority class than lower priority class with a fixed quality-spacing, i.e., consistent service differentiation [DOV02][LEU01]. The PPBS scheme combines the deflection routing, the segmentation and the probabilistic preemption approaches. In PPBS scheme, an arriving burst can use any free wavelength regardless of its priority class. If no free wavelength is available, a probabilistic parameter, which is associated with the class, allows the arriving burst to preempt an entire lower-priority burst or segment it and preempt the overlapped in a probabilistic fashion. The preempted burst or segment will not be dropped. Instead, it will be assigned to other links using the deflection routing approach. By tuning the probabilistic parameters, the loss rate spacing between different priority classes can be controlled. Like the PPS scheme, the drawback of this scheme is also the scalability problem.

## **2.6.2 Absolute QoS Differentiation Schemes**

Up to date, most of the QoS differentiation schemes are in the relative QoS category. Although the relative QoS differentiation schemes can guarantee that a high-priority class

experiences better performance than a low-priority class does, they do not offer any hard upper-bound on the QoS performance required by some applications. In some cases, online applications such as VoIP and videoconference need the system to provide a worst-case guarantee on loss and delay. Today's mission-critical Internet makes it become essential to support absolute QoS differentiated services in OBS networks, which guarantee the strict upper-bound on QoS performance of different traffic types based on their needs. Although an efficient absolute QoS differentiation mechanism is urgently needed, there are only a few schemes in this research area up to now.

**Preemptive Scheme [PHU04][PHU06]:** This scheme defines the distance-to-threshold of a class as the difference between the loss threshold and the monitored loss rate of the class. Every core node maintains a list of all the service classes in the OBS network. When a burst header arrives at a core node and fails to reserve an output wavelength, the node checks the list and picks the class with the maximum distance-to-threshold among the classes to which the incoming burst and the overlapped bursts belong. If the incoming burst belongs to the class with the maximum distance-to-threshold, it will be dropped; otherwise, the scheduled burst belonging to the class with the maximum distance-to-threshold will be preempted by the incoming burst. This scheme keeps the loss rate of every class below its predefined threshold. However, it ignores the performance of the BE class traffic, which is expected to experience a loss rate as low as possible.

**Dynamic virtual lambda partitioning (DVLP) Scheme [KIM03][KIM05]:** This scheme dynamically divides the wavelengths of an output link into wavelength groups

depending on QoS requirements and allocates each group to a priority class. Furthermore, the wavelength reservation policies of different classes are different. A high-priority class can access the wavelength resources within its own wavelength group as well as the resources in the wavelength group of the lower priority classes. The wavelength groups are expanded or contracted based on the QoS requirements of their corresponding classes. Whenever a high-priority class needs to expand its wavelength group, it always takes a wavelength from the wavelength group of the lowest-priority class (i.e., the BE class). This scheme can be viewed as a complete partitioning of the output link into several “pipes” whose capacities are adjusted as necessary. Because resources are assigned to different wavelength groups in wavelength level, which is a coarse granularity, usually there is some “spare” bandwidth in the wavelength groups of the high-priority classes while their loss requirements are guaranteed. However, the BE class traffic can never access the “spare” bandwidth. Therefore, the high-priority classes may experience “unnecessarily” low loss rates while the BE class suffers from a high loss rate.

**Proactive Wavelength Preemption [PHU07]:** This is a preemption-based absolute QoS differentiation scheme. This scheme allows an arriving burst, no matter belonging to a PG class or the BE class, to reserve whatever wavelength available. In this scheme, the arriving bursts of a PG class, whose loss rate is approaching the threshold, can preempt scheduled BE bursts. As a result, the loss requirement of the PG class is guaranteed. However, this scheme does not give emphasis to the performance of the BE class. Even when the loss rate of a PG class is much lower than its threshold, the scheduled bursts of the PG class can never be preempted by any arriving BE bursts. Thus, the PG class consumes more bandwidth

unnecessarily, and the loss rate of the BE class is higher.

**Early Drop Scheme (EDS):** Zhang et al. proposed the EDS scheme in [ZHA03a]. In this scheme, the low-priority bursts can be dropped early to prevent them from competing with the high-priority bursts. This occurs when the high-priority class is in danger of breaching its threshold. As a result, the high-priority class traffic experiences a lower effective load and the bursts of the high-priority class get a better chance to reserve bandwidth successfully. Hence, the loss rate of the high-priority class is reduced. The problem of the EDS is that the BE traffic is over-penalized to make room for the high-priority class to guarantee its loss rate. As a result, the BE class suffers from high loss rate and the bandwidth utilization is poor.

As we know, in the above absolute QoS differentiation schemes, the performance of the BE class is ignored and it suffers from high loss rate. To improve the system performance in terms of the loss rate of the BE class, Zhang et al. integrated the EDS scheme and wavelength grouping schemes in [ZHA03b]. In the integrated schemes, every priority-guaranteed (PG) class is provided a group of wavelengths whose number is calculated based on Erlang-B formula. The residual wavelengths are assigned to the BE class. Like in the pure EDS scheme, the BE bursts are probabilistically “dropped”. The difference is that the probabilistically “dropped” BE bursts can try to reserve bandwidths in its own wavelength group while the BE bursts that are not probabilistically “dropped” are allowed to be treated as high-priority bursts and reserve the bandwidth in the wavelength group of the high-priority class. Hence, the loss rate of the BE class is reduced and the bandwidth utilization is improved.

However, in the EDS and the integrated schemes, the BE bursts are probabilistically

dropped based on an early-drop-probability  $p^{ED}$ , which is defined as a linear function of the loss rate of the high-priority class. As the loss rate of the high-priority class is approaching its threshold,  $p^{ED}$  is getting larger and larger until the loss rate of the high-priority class is violated, when  $p^{ED}$  is set as 1 and all BE bursts are dropped. Actually, even when the loss rate of the high-priority class is violated, on the wavelengths dedicated to the high-priority class still exist some gaps that could have been used by the BE bursts. This is because the resources are allocated to different classes on wavelength level, which is a coarse granularity. Thus, there still exists performance improvement room in terms of the loss rate of the BE class and the bandwidth utilization.

## **2.7 Summary**

This chapter has first provided a background of the OBS paradigm. Then, an overview of the OBS paradigm and the different OBS architectures has been presented. Scheduling algorithms and contention resolution schemes are important issues in OBS networks and closely related to QoS differentiation, which is the focus of this thesis. Hence, we have introduced existing scheduling algorithms and contention resolution schemes. Finally, we have presented existing relative QoS differentiation schemes and absolute QoS differentiation schemes. Specifically, the pros and cons of different schemes have been examined.

# Chapter 3

## Per-hop Absolute QoS Differentiation

### 3.1 Introduction

Our ultimate objective in this thesis is to develop an E2E absolute QoS differentiation scheme. First, we need to realize absolute QoS differentiation on a per-hop basis. In this chapter, we first present a novel preemption-based absolute QoS differentiation scheme, which is called Reserve-and-Preempt Scheme (RPS). RPS aims at minimizing the performance penalty of the BE class traffic while satisfying the loss requirement of every PG class. An analytical model of RPS is also developed based on Markov Chains.

In order to support networks with multiple PG classes, we integrate RPS with wavelength grouping schemes (SWG and DWG) and present the RPS-SWG and the RPS-DWG schemes. Furthermore, to satisfy the loss requirements of the lower-priority PG classes under heavy

load, RPS-SWG and RPS-DWG are extended to RPS-ESWG and RPS-EDWG, respectively. Finally, we present Extended Reserve-and-Preempt Scheme (ERPS), which is easier to implement than those schemes that are integrated with the wavelength grouping schemes.

## **3.2 Reserve-and-Preempt Scheme (RPS)**

### **3.2.1 Basic Idea of RPS**

As we have introduced in Chapter 2, while trying to satisfy the loss requirements of the PG classes in OBS networks, most of the existing absolute QoS differentiation schemes ignore the performance of the BE class. For example, to guarantee the loss rate of every PG class in an OBS network, early-drop scheme (EDS) [ZHA03a] drops the BE class bursts if the loss rate of a PG class approaches its threshold, even when there are idle wavelengths available. Thus, the BE class is over-penalized. To reduce the loss rate of the BE class, Zhang et al. integrated EDS with dynamic wavelength grouping (DWG) scheme and proposed EDS-DWG scheme in [ZHA03b]. The EDS-DWG scheme allocates a group of wavelengths to each PG class, and some of the BE class bursts are allowed to be treated as PG class bursts and share the bandwidth of the PG class. However, because of the coarse granularity in wavelength grouping, there always exists some spare bandwidth on the wavelengths that cannot be utilized by the BE class bursts, especially when the loss threshold of the PG class is endangered.

To improve the performance of the BE class, we propose a new preemption-based QoS differentiation scheme, which is called Reserve-and-Preempt Scheme (RPS). The objective of

the RPS scheme is to keep the loss rate of every PG class not only below its preset threshold, but also as close to it as possible. The main difference of RPS from the EDS-DWG scheme is that RPS allows the BE class bursts to share the bandwidth with the PG class bursts in an UNRESTRICTED manner. In other words, RPS allows an arriving BE class burst to reserve bandwidth even when the PG classes are breaching their respective thresholds, as long as there are idle wavelengths available. However, a PG class burst can preempt a scheduled BE class burst whenever it is necessary. As a result, the total idle time on a wavelength can be kept as short as possible. Moreover, a BE class burst can even preempt a scheduled PG class burst if the PG class is not in danger of violating its loss threshold. As a result, while each PG class loss rate is kept below its threshold, the spare bandwidth is efficiently utilized by the BE class bursts.

In the proposed RPS scheme, if there is an idle wavelength available, an arriving burst can always reserve it, no matter to what class the arriving burst belongs; otherwise, contention occurs. In order to keep the loss rate of every PG class below its threshold, the loss rate of each class on each output link is monitored online at every core node. For class  $C_i$ , there are two counters  $D_{C_i}$  and  $R_{C_i}$ , which keep the number of dropped bursts and the number of request bursts of class  $C_i$  respectively. The monitored loss rate of class  $C_i$  is calculated as  $p_{C_i} = D_{C_i} / R_{C_i}$ .

Then, we need to define a Distance-to-Threshold (*DTT*) for every PG class.  $DTT_{C_i}$  is defined as the distance from its monitored loss rate to its preset threshold  $\overline{p_{C_i}}$ , i.e.

$$DTT_{C_i} = \begin{cases} \overline{p_{C_i}} - p_{C_i} & \overline{p_{C_i}} > p_{C_i} \\ 0 & \overline{p_{C_i}} \leq p_{C_i} \end{cases} \quad (3.1)$$

Here, note that  $DTT_{C_i}$  is set to zero if the loss threshold is violated.

At every core node, the system maintains a database for all the classes at each output link. Whenever a burst is scheduled, dropped or preempted, the DTT of the class the burst belonging to is calculated and the database is updated. Whether to drop an arriving burst or let it to preempt a scheduled burst depends on the DTTs of the classes to which the contending bursts belong. The PG burst that is dropped or preempted must belong to the class with the maximum DTT.

## 3.2.2 Contention Resolution

As we mentioned before, when a burst arrives at a core node, if there are idle wavelengths available, the arriving burst is simply scheduled on one of the idle wavelengths. Otherwise, contention is unavoidable.

### 3.2.2.1 PG Class Burst Arrival

Figure 3.1 shows the contention scenarios when a PG class burst arrives at an intermediate node in the RPS scheme. When the PG class burst arrives and all wavelengths are busy, there are three scenarios as follows:

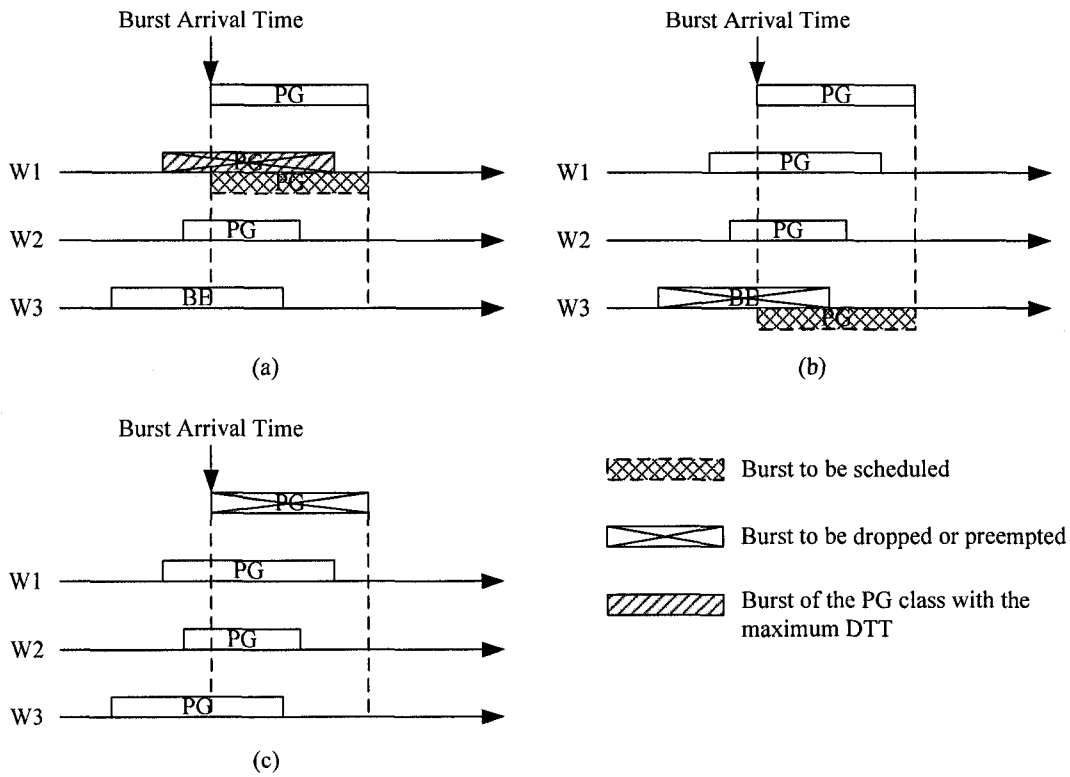


Figure 3.1 Illustration of RPS Scheme: Contention Scenarios of PG Class Burst Arrival

1. The PG class burst arrives, and an overlapped PG class burst with the maximum DTT is found. In this case, the arriving burst will preempt the scheduled PG class burst with the maximum DTT, as shown in Figure 3.1(a).
2. When the PG class burst arrives, the burst with the maximum DTT is the arriving burst itself and there is a scheduled BE class burst that is overlapped (Figure 3.1(b)). In this case, the arriving burst will preempt the BE class burst.
3. When the PG class burst arrives, the burst with the maximum DTT is the arriving burst itself but there are no scheduled BE class bursts overlapped (Figure 3.1(c)). In this case, the arriving burst will be dropped.

### **3.2.2.2 BE Class Burst Arrival**

If the arriving burst is of the BE class and all the wavelengths are busy, we have two options: drop the arriving BE class burst or let the arriving BE class burst preempt an overlapped PG class burst.

#### **3.2.2.2.1 BE Class Burst Dropping Approach (BED)**

If all the wavelengths are busy when a BE class burst arrives, the first option is to drop the arriving BE class burst. This approach is easy to implement. If the traffic load is heavy and the loss thresholds of the PG classes are in danger of being violated, dropping the arriving BE class burst is reasonable. However, when the traffic load is light and the loss rates of the PG classes are lower than their respective thresholds, simply dropping the arriving BE class burst induces inefficient bandwidth utilization and makes the loss rate of the BE class higher.

#### **3.2.2.2.2 BE Burst Preempting Approach (BEP)**

To address the above problem, we can allow an arriving BE class burst to preempt a burst belonging to the PG class with the maximum DTT. As shown in Figure 3.2, when a BE class burst arrives at a core node and all the wavelengths are busy, there are two contention scenarios:

1. At least one of the overlapped bursts belongs to a PG class whose loss rate threshold is not violated ( $DTT > 0$ ) (Figure 3.2(a)). In this case, the overlapped burst belonging to the PG class with the maximum DTT will be preempted.

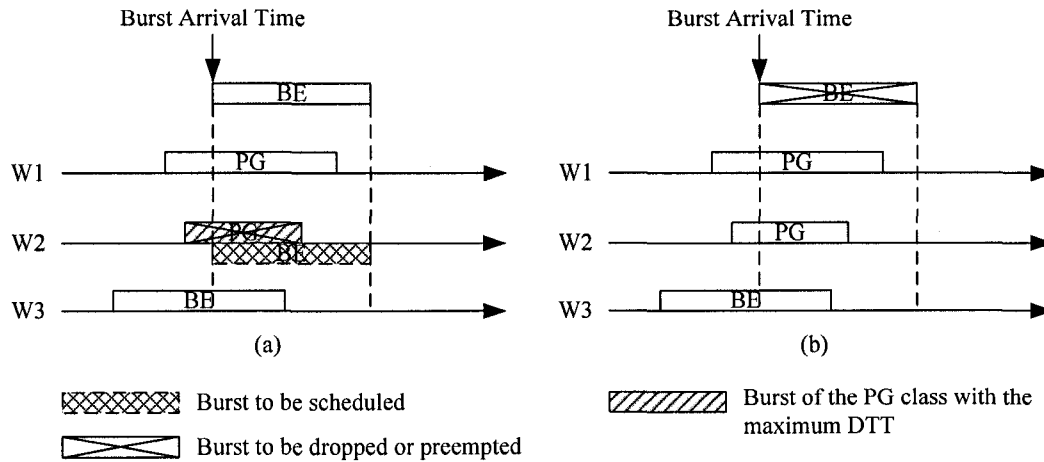


Figure 3.2 Illustration of RPS Scheme: Contention Scenarios of BE Class Burst Arrival

2. The DTTs of the PG classes, to which the overlapped bursts belong, equal zero (Figure 3.2(b)). In other words, the loss threshold of every overlapped PG class is violated, and thus all the overlapped PG class bursts cannot be preempted. In this case, the arriving BE class burst will be dropped. Here, note that a BE class burst never preempt another BE class burst.

Obviously, the BEP approach can provide the BE class traffic more bandwidth than the BED approach under lower traffic load.

### 3.2.2.3 Stopping Over-preempting PG class Bursts

In the RPS scheme with BEP approach, a scheduled PG class burst could be preempted by an arriving burst belonging to the BE class or another PG class whose DTT is smaller. However, bursts of a PG class should not keep being preempted. Otherwise, the bursts of the PG class will be over-preempted and the loss rate of the PG class cannot be guaranteed. When is the PG class bursts supposed to stop being preempted? We have two options here.

### 3.2.2.3.1 Stopping Over-preempting PG Class Bursts by a Hard Threshold (SPT)

To prevent a PG class  $C_i$  from being over-preempted, the simplest approach is to use the loss threshold as a hard threshold. Suppose a burst arrives and contends for bandwidth with a scheduled burst of class  $C_i$ , with the maximum DTT. If the monitored loss rate of class  $C_i$  is higher than its loss threshold (i.e.,  $DTT_i = 0$ ), a burst of class  $C_i$  will not be preempted and the arriving burst will be dropped. On the other hand, if  $DTT_i > 0$  and the arriving burst is of the BE class, the scheduled burst will be definitely preempted.

With this approach, bursts of class  $C_i$  are prevented from being preempted only after the loss rate has reached or exceeded its threshold ( $p_{C_i} \geq \overline{p_{C_i}}$ ). As a result, the loss rates of the PG classes may exceed their thresholds before the SPT mechanism is triggered. Obviously, this is not desirable.

### 3.2.2.3.2 Stopping Over-preempting PG Class Bursts Gradually (SPG)

To overcome the drawback of the above approach, we define  $R_{C_i}$  as the scheduled-burst-preemption (SBP) probability of class  $C_i$  (i.e., the probability that a burst of PG class  $C_i$  is preempted). Whenever a burst of class  $C_i$  needs to be preempted, a random number  $r$  is generated. If  $r < R_{C_i}$ , the burst will be preempted; otherwise, the arriving burst will be dropped. To define  $R_{C_i}$ , we set a guard space  $\delta$ , and make the SBP probability  $R_{C_i}$  decrease linearly as the loss rate of class  $C_i$  approaches its threshold. Thus,

$$R_{C_i} = \begin{cases} 1 & p_{C_i} < \overline{p_{C_i}} \\ (\overline{p_{C_i}} - p_{C_i}) / \delta & \overline{p_{C_i}} - \delta \leq p_{C_i} < \overline{p_{C_i}} \\ 0 & p_{C_i} \geq \overline{p_{C_i}} \end{cases} \quad (3.2)$$

Thus, the bursts of an endangered PG class can lower its probability of being preempted before the loss rate of the PG class reaches its threshold. Therefore, the PG class bursts can get a higher chance to get through, and thus, the PG class can be prevented from violating its threshold.

### 3.3 Analytical Model of RPS Scheme

In this section, we develop an analytical model for the proposed RPS scheme. To make it simpler, without loss of generality, we assume there are two service classes in the system, where class  $C_0$  is the PG class and class  $C_1$  is the BE class.

The analytical model is developed using Markov chains. Figure 3.3 is the Markov chain for the RPS scheme. We suppose that there are  $w$  wavelengths on a link. Let  $x_0$  be the number of wavelengths reserved by class  $C_0$  bursts, and  $x_1$  be the number of wavelengths occupied by class  $C_1$  bursts. Thus, the state can be defined as  $S = \{x_0, x_1\}$ , and the link can be treated as a continuous time Markov chain. From Figure 3.3, we can get the state transition rates as follows:

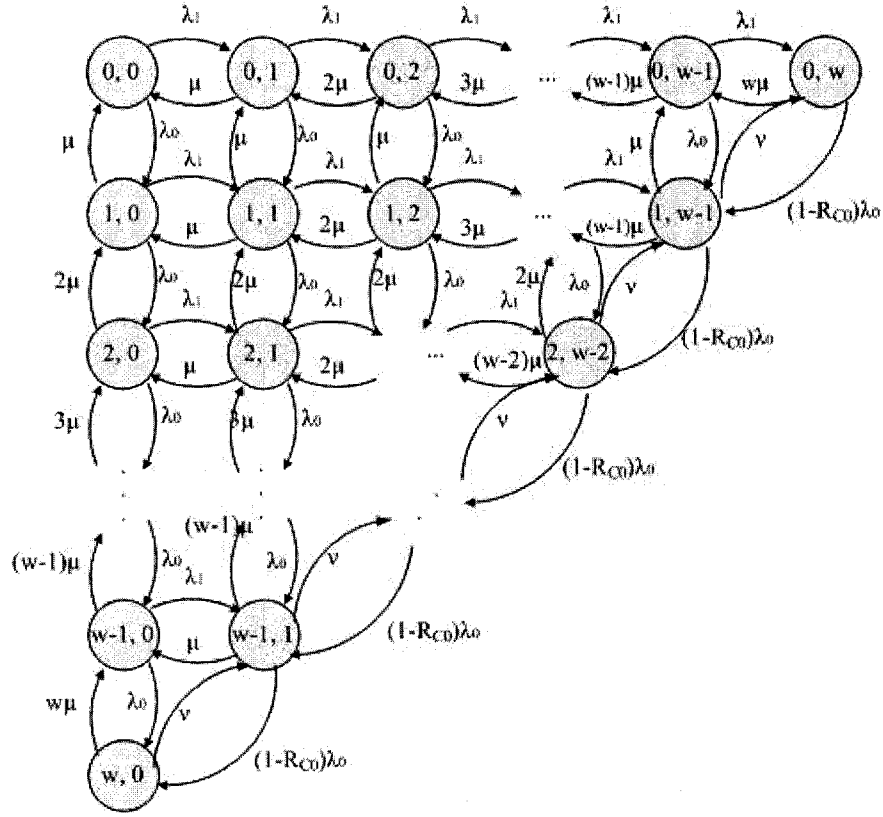


Figure 3.3 Markov Chain for RPS Scheme

$$\begin{aligned}
 q_{(x_0, x_1)(x_0+1, x_1)} &= \begin{cases} \lambda_0 & x_0 + x_1 < w \\ 0 & \text{otherwise} \end{cases} \\
 q_{(x_0, x_1)(x_0, x_1+1)} &= \begin{cases} \lambda_1 & x_0 + x_1 < w \\ 0 & \text{otherwise} \end{cases} \\
 q_{(x_0, x_1)(x_0-1, x_1)} &= \begin{cases} x_0 \mu & x_0 + x_1 \leq w, x_0 > 0 \\ 0 & \text{otherwise} \end{cases} \\
 q_{(x_0, x_1)(x_0, x_1-1)} &= \begin{cases} x_1 \mu & x_0 + x_1 \leq w, x_1 > 0 \\ 0 & \text{otherwise} \end{cases} \\
 q_{(x_0, x_1)(x_0-1, x_1+1)} &= \begin{cases} \nu & x_0 + x_1 = w, x_0 > 0 \\ 0 & \text{otherwise} \end{cases} \\
 q_{(x_0, x_1)(x_0+1, x_1-1)} &= \begin{cases} \lambda_0 & x_0 + x_1 = w, x_1 > 0 \\ 0 & \text{otherwise} \end{cases}
 \end{aligned} \tag{3.3}$$

where  $\lambda_0$  and  $\lambda_1$  are the arrival rates of class  $C_0$  and class  $C_1$  respectively.  $\mu$  is the

transmission rate on a single wavelength. In addition,  $\nu$  is the rate on which the BE class bursts preempt the PG class bursts when there are no idle wavelengths available and there is at least one  $C_0$  burst scheduled. It can be defined as follows:

$$\nu = \lambda_1 \cdot R_{C_0}. \quad (3.4)$$

From the above transition rates, the steady state probabilities  $p(x_0, x_1)$  can be solved. A burst of class  $C_0$  (PG class) can be lost in two cases:

1. When the class  $C_0$  burst arrives, all the wavelengths are occupied by other class  $C_0$  bursts. The probability that all wavelengths are occupied by class  $C_0$  bursts is  $p(w, 0)$ .
2. The class  $C_0$  burst, which has been scheduled, is preempted by a class  $C_1$  (BE class) burst. Here the probability is  $\frac{\lambda_1}{\lambda_0} \cdot R_{C_0} \cdot \sum_{i=1}^w p(i, w-i)$ .

Thus, we can get the loss rate of class  $C_0$  by

$$p_{C_0} = p(w, 0) + \frac{\lambda_1}{\lambda_0} \cdot R_{C_0} \cdot \sum_{i=1}^w p(i, w-i) \quad (3.5)$$

Similarly, a class  $C_1$  (BE class) burst can be lost in three cases:

1. When a BE class burst arrives, all the wavelengths are busy with serving other BE class bursts. In this case, the arriving BE burst has to be dropped. The probability

is  $p(0, w)$ .

2. When the BE class burst arrives, the PG class burst with the maximum DTT is approaching its threshold. In this case, the arriving BE class burst is dropped based on the DTT of the overlapped PG class. The smaller the maximum DTT, the more BE bursts we want to drop. We define  $(1 - R_{C_0}) \cdot \sum_{i=1}^w p(i, w - i)$  as the probability to drop an arriving BE burst in this case.
3. A scheduled BE class burst is preempted by a PG class burst when the PG class burst arrives and all wavelengths are busy. We want more PG bursts to preempt scheduled BE bursts when the loss rate of the PG class is approaching its loss threshold. On the contrary, if the loss rate of the PG class is much lower than the loss threshold, we want the PG bursts to be dropped instead of preempting the BE bursts, in order to provide more bandwidth for the BE bursts. Thus, the probability that a BE burst is preempted can be expressed as  $(1 - R_{C_0}) \cdot \frac{\lambda_0}{\lambda_1} \cdot \sum_{i=0}^{w-1} p(i, w - i)$ .

Therefore, the loss rate of class  $C_l$  can be calculated as

$$p_{C_l} = p(0, w) + (1 - R_{C_0}) \cdot \sum_{i=1}^w p(i, w - i) + (1 - R_{C_0}) \cdot \frac{\lambda_0}{\lambda_1} \cdot \sum_{i=0}^{w-1} p(i, w - i) \quad (3.6)$$

### 3.4 Supporting Multiple PG Classes

In RPS, contentions are resolved based on DTTs. Once the traffic load gets heavy enough, the

loss rates of all the PG classes may exceed their respective thresholds, and the DTTs of all the PG classes may become 0. As a result, different PG classes cannot be differentiated according to DTTs anymore. In this case, we hope that at least the highest-priority class can be satisfied of its loss requirement if we cannot guarantee the loss rates of all the PG classes at the same time.

### 3.4.1 Integrating RPS with Wavelength Grouping Mechanisms

Under heavy traffic load, to make sure that at least the highest-priority class can experience its guaranteed loss rate, we can integrate the RPS scheme with wavelength grouping mechanisms and provide each of the PG classes with a minimum number of wavelengths. According to the Erlang B formula, to guarantee a loss rate  $p_{C_i}$  under load  $L_i$ , a PG class  $C_i$  needs to be allocated at least  $w_i^R$  wavelengths:

$$p_{C_i}(w_i^R, L_i) = \frac{\frac{L_i^{w_i^R}}{w_i^{R!}}}{\sum_{m=0}^{w_i^R} \frac{L_i^m}{m!}}. \quad (3.7)$$

However, when the traffic load gets heavy, the limited number of wavelengths at a link cannot meet the requests of all the PG classes (i.e.,  $w < \sum_{i=0}^{n-1} w_i^R$ , where  $w$  is the total number of wavelengths on the link,  $w_i^R$  is the requested number of wavelengths of class  $C_i$ , and  $n$  is the total number of PG classes). In this case, not every PG class can be allocated its

requested number of wavelengths. A PG class whose allocated number of wavelengths  $w_i^A$  is less than its requested number of wavelengths  $w_i^R$  will suffer from a loss rate higher than its threshold. To make sure the highest priority class experiences its guaranteed loss rate, it can be allocated the number of wavelengths it requests, while the lower priority PG classes get the residual wavelengths. Suppose we have  $n$  PG classes, and class  $C_0$  has the highest priority, the wavelength allocation mechanism is as follows:

$$w_0^A = \begin{cases} w_0^R & w > w_0^R \\ w & w \leq w_0^R \end{cases}, \quad (3.8)$$

and

$$w_i^A = \begin{cases} w_i^R & w - \sum_{m=0}^{i-1} w_m^A > w_i^R \\ w - \sum_{m=0}^{i-1} w_m^A & w - \sum_{m=0}^{i-1} w_m^A \leq w_i^R \end{cases}, \quad (3.9)$$

where  $i = 1, \dots, n-1$ .

Therefore, the higher priority classes which are allocated their requested number of wavelengths (i.e.,  $w_i^A = w_i^R$ ) are called satisfied classes, and the other PG classes whose requested number of wavelengths are not satisfied (i.e.,  $w_i^A < w_i^R$ ) are called unsatisfied classes.

There are two wavelength-grouping schemes: static wavelength grouping (SWG) and dynamic wavelength grouping (DWG).

### 3.4.1.1 Integrated Scheme of RPS and SWG (RPS-SWG)

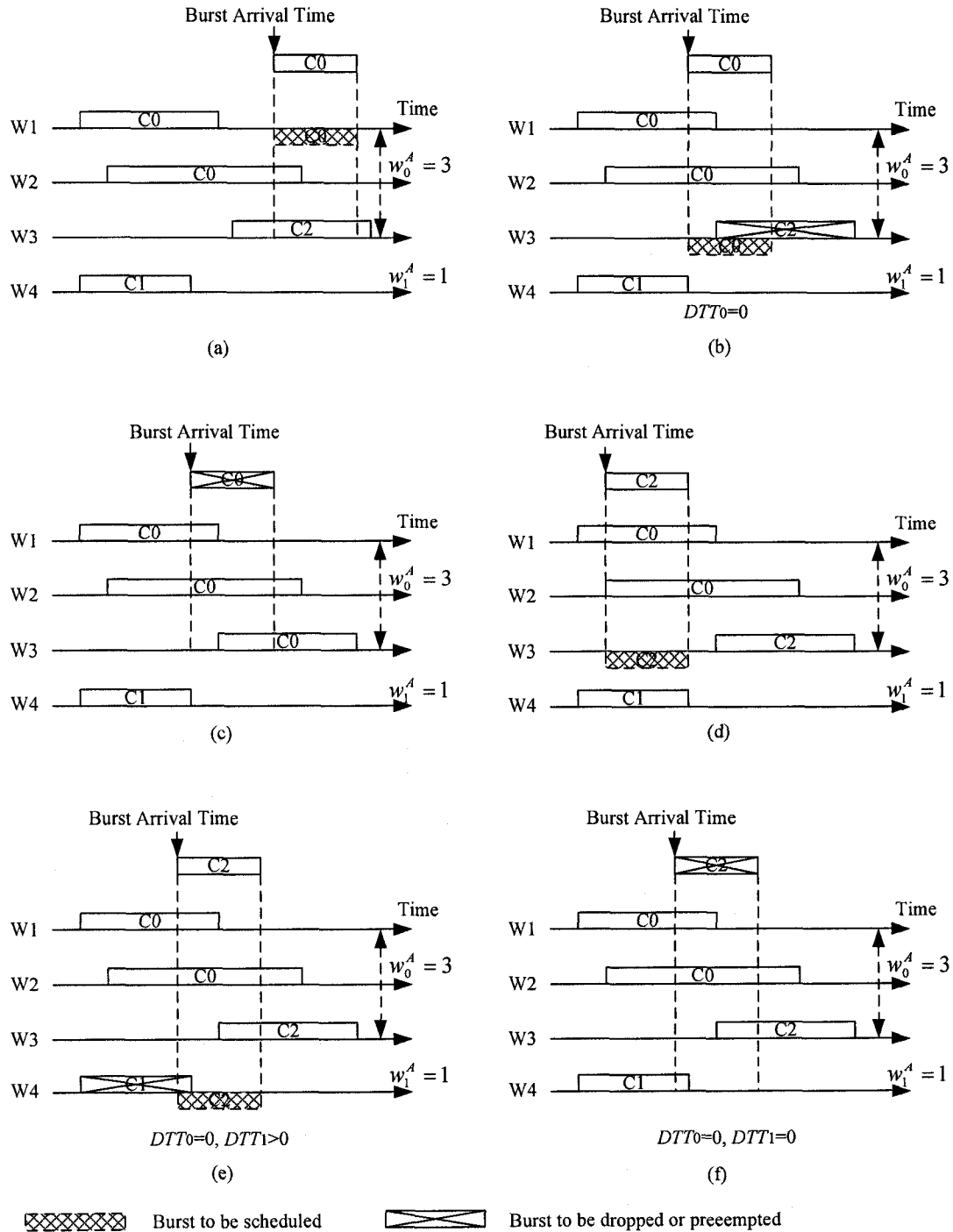


Figure 3.4 Illustration of RPS-SWG Scheme

With SWG, each PG class is allocated a fixed set of wavelengths, and bursts belonging to a PG class can use only the fixed set of wavelengths that are dedicated to its class. An arriving PG class burst will be dropped when all the wavelengths allocated to its class are occupied, even if there are wavelengths that do not belong to its class available.

On the other hand, an arriving BE class burst can reserve any available wavelength. In addition, the arriving BE class burst can preempt a scheduled burst of a PG class  $C_i$  according to its scheduled-burst-preemption probability  $R_{C_0}$ . However, if the BE class burst has been scheduled on a wavelength that belongs to a PG class, it could be preempted by an arriving burst of that PG class when there are no free wavelengths available and the loss threshold of the PG class is in danger of being breached.

As shown in Figure 3.4, suppose we have two PG classes ( $C_0$  and  $C_1$ ) and a BE class ( $C_2$ ) in the system.  $W1$ ,  $W2$  and  $W3$  are allocated to  $C_0$ , and  $W4$  is dedicated to  $C_1$ . In Figure 3.4(a), the arriving  $C_0$  burst is scheduled on  $W1$ , because  $W1$  is idle and belongs to  $C_0$ . In Figure 3.4(b), when the  $C_0$  burst arrives, the loss threshold of  $C_0$  is breached and  $W3$  is occupied by a burst of the BE class ( $C_2$ ). Thus, the arriving burst preempts the  $C_2$  burst on  $W3$ . As shown in Figure 3.4(c), all the wavelengths allocated to class  $C_0$  are occupied by bursts of class  $C_0$ , the arriving burst has to be dropped even though there is an idle wavelength ( $W4$ ) which is allocated to the other PG class ( $C_1$ ). In Figure 3.4(d), the arriving burst of the BE class ( $C_2$ ) is scheduled on wavelength  $W1$ , which is idle. In Figure 3.4(e), suppose the loss threshold of class  $C_1$  is not violated (i.e.,  $DTT_1 > 0$ ), the  $C_1$  burst on  $W4$  could be preempted by the arriving  $C_2$  burst. However, if the loss thresholds of both  $C_0$  and  $C_1$  are violated, the arriving

$C_2$  burst will be dropped, as Figure 3.4(f) shows.

### 3.4.1.2 Integrated Scheme of RPS and DWG (RPS-DWG)

With DWG, each PG class is allocated a fixed number of wavelengths, but not necessarily a fixed set of wavelengths. When a burst belonging to a PG class  $C_i$  arrives, it can be dynamically scheduled onto any available wavelength as long as the number of wavelengths occupied by class  $C_i$  bursts is less than the number of wavelengths allocated to class  $C_i$  (i.e.,  $w_i^o < w_i^A$ ).

With RPS-DWG, just like with RPS-SWG, an arriving BE class burst can reserve any idle wavelength. Moreover, when an arriving BE class burst is contending with a scheduled burst of a PG class  $C_i$ , the BE class burst can preempt the scheduled burst according to the scheduled-burst-preemption probability of class  $C_i$  ( $R_{C_i}$ ).

However, a scheduled BE class burst could be preempted by an arriving burst of PG class  $C_i$  if all the following three conditions are satisfied:

1. There are no idle wavelengths available.
2. For class  $C_i$ , the number of occupied wavelengths is less than the allocated number of wavelengths (i.e.,  $w_i^o < w_i^A$ ).
3. The loss threshold of class  $C_i$  is being violated (i.e.,  $DTT_i = 0$ ).

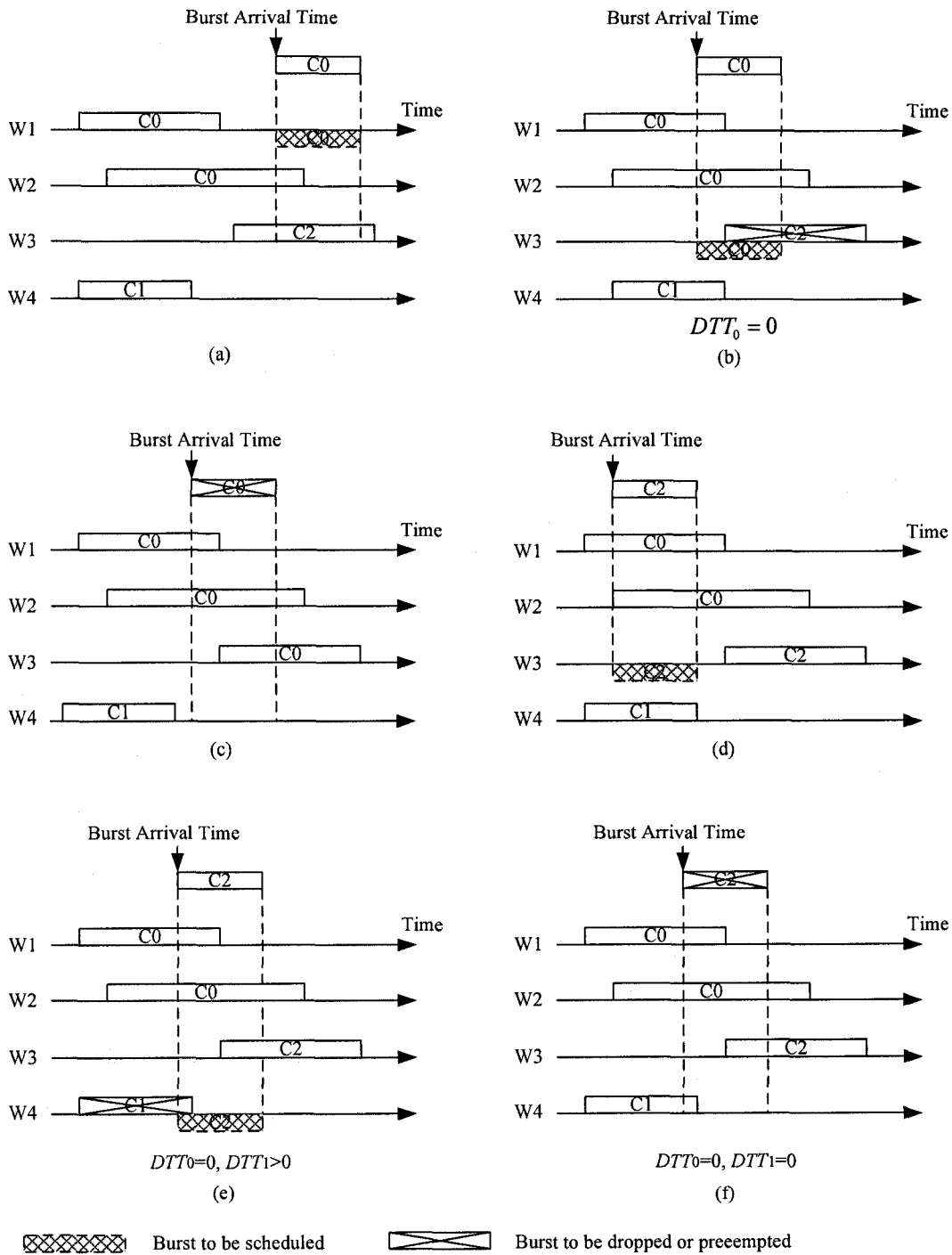


Figure 3.5 Illustration of RPS-DWG Scheme

Figure 3.5 shows the contention scenarios in the RPS-DWG scheme.  $C_0$  and  $C_1$  are PG

classes, and  $C_2$  is the BE class. There are 4 wavelengths in total, and  $w_0^A = 3$  and  $w_1^A = 1$ . In Figure 3.5(a), when the  $C_0$  burst arrives,  $w_0^O < w_0^A$  and  $W1$  is idle, thus the arriving burst is scheduled on  $W1$ . In Figure 3.5(b), because  $w_0^O < w_0^A$  and  $DTT_0 = 0$ , the arriving  $C_0$  burst needs to preempt the  $C_2$  burst on  $W3$ . In Figure 3.5(c), the arriving  $C_0$  burst is dropped because  $w_0^O = w_0^A$  and all wavelengths are busy. The arriving  $C_2$  burst reserves the idle wavelength  $W3$  in Figure 3.5(d). In Figure 3.5(e), no wavelength is available to service the arriving  $C_2$  burst, but class  $C_1$  is not endangered yet ( $DTT_1 > 0$ ). Thus, the arriving  $C_2$  burst preempts the scheduled  $C_1$  burst on  $W3$  with a probability  $R_{C_1}$ . In Fig 3-5(f), the arriving  $C_2$  burst is dropped because no wavelength is available and all the PG classes are breaching their thresholds.

Comparing the two integrated schemes, we can observe that the RPS-SWG scheme is easier to implement, but the RPS-DWG scheme is more flexible since it schedules an arriving burst based on real-time wavelength status. In RPS-DWG, an arriving burst can have more candidate wavelengths to choose from and is more likely to be scheduled successfully, thus the system performance can be improved. This can be verified in Chapter 5 by simulation results.

### **3.4.2 Integrating RPS with Extended Wavelength Grouping Mechanisms**

With RPS-SWG and RPS-DWG, as long as a PG class can be allocated the number of

wavelengths it requests, its loss rate can be guaranteed to be kept below its threshold. However, when the traffic load is heavy, the limited number of wavelengths cannot meet the requests of all the classes (i.e.,  $w < \sum_i w_i^R$ ). Thus, RPS-SWG and RPS-DWG satisfy the requirements of the higher-priority classes first, and the lower-priority classes suffer from high loss rates because their requested number of wavelengths cannot be satisfied. At the same time, while a satisfied PG class is allocated its requested number of wavelengths to guarantee its loss rate, there is always some spare bandwidth on the wavelengths. This is because the wavelengths are allocated to the classes in a coarse granularity (wavelength) level. Unfortunately, the spare bandwidth cannot be utilized by bursts of the unsatisfied PG classes.

To efficiently utilize the spare bandwidth of the satisfied PG classes and make each of the unsatisfied PG classes experience a lower loss rate, we can allow the unsatisfied PG classes to share the wavelengths allocated to the satisfied PG classes. Thus, we have the following two schemes: integrated scheme of RPS and extended SWG (RPS-ESWG) and integrated scheme of RPS and extended DWG (RPS-EDWG).

### **3.4.2.1 Integrated Scheme of RPS and Extended SWG (RPS-ESWG)**

In this scheme, if there are idle wavelengths available, an arriving burst of a satisfied PG class can reserve only a wavelength that is dedicated to the class. An arriving burst of an unsatisfied PG class can reserve not only the wavelengths belonging to its own class, but also those belonging to the satisfied PG classes. A burst of the BE class can reserve any

wavelengths.

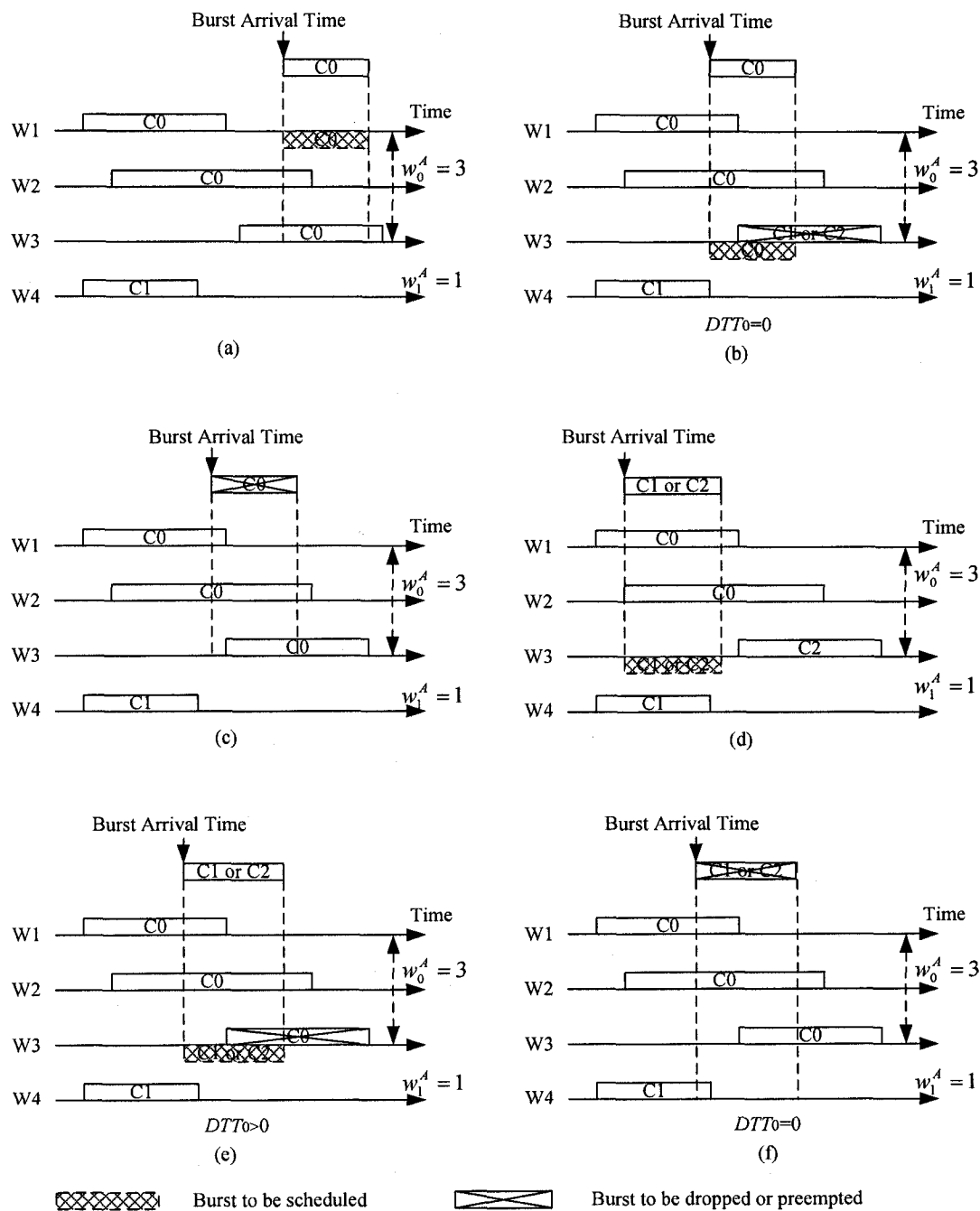


Figure 3.6 Illustration of RPS-ESWG Scheme

When contention occurs, however, an arriving burst of a satisfied PG class can preempt

an unsatisfied PG class burst or a BE class burst in its own wavelength group if the loss threshold of the satisfied PG class is endangered. On the other hand, an arriving burst of an unsatisfied PG class can preempt a BE class burst in its own wavelength group, or, it can preempt a scheduled burst of a satisfied PG class whose loss threshold is not endangered.

Figure 3.6 illustrates the RPS-ESWG scheme. In Figure 3.6, suppose there are three classes in the system, where  $C_0$  is the satisfied PG class ( $w_0^A = w_0^R = 3$ ),  $C_1$  is the unsatisfied PG class ( $w_1^A = 1$  and  $w_1^R = 2$ ), and  $C_2$  is the BE class.  $W1$ ,  $W2$  and  $W3$  are allocated to class  $C_0$ , and  $W4$  is allocated to class  $C_1$ . In Figure 3.6(a), when the class  $C_0$  burst arrives, an idle wavelength  $W1$  is available in its wavelength group. Thus, the burst is scheduled in  $W1$ . In Figure 3.6(b), when the  $C_0$  burst arrives, all wavelengths are busy and class  $C_0$  is violating its threshold. Therefore, the arriving  $C_0$  burst can preempt a burst of class  $C_1$  or  $C_2$ , which has been scheduled in one of the wavelengths allocated to class  $C_0$ . If all the dedicated wavelengths are busy with servicing  $C_0$  bursts when a  $C_0$  burst arrives, the arriving burst is dropped as shown in Figure 3.6(c). In Figure 3.6(d), when a burst of the unsatisfied PG class ( $C_1$ ) or the BE class ( $C_2$ ) arrives, the wavelength allocated to class  $C_1$  is occupied by a  $C_1$  burst, and there is a free wavelength  $W3$  that is allocated to  $C_0$ . In this case, the arriving burst can reserve  $W3$ . Here, we note that if the arriving burst is of class  $C_1$ , it can be scheduled on the idle wavelength  $W3$ , which is allocated to  $C_0$ . This is because that  $C_1$  is an unsatisfied PG class and its number of occupied wavelengths is less than its requested number of wavelengths (i.e.,  $w_1^O < w_1^R$ ). In Figure 3.6(e), when a  $C_1$  or  $C_2$  burst arrives, all the wavelengths are busy, and class  $C_0$  is not violating its threshold. Thus, the arriving burst can

preempt a scheduled  $C_0$  burst and reserve wavelength  $W_3$ , which is allocated to class  $C_0$ . In Figure 3.6(f), all wavelengths are busy, and the loss threshold of class  $C_0$  is being violated. In this case, the arriving  $C_1$  or  $C_2$  burst has to be dropped.

### 3.4.2.2 Integrated Scheme of RPS and Extended DWG (RPS-EDWG)

In RPS-EDWG, when there are idle wavelengths, an arriving PG class burst, no matter belonging to a satisfied PG class or an unsatisfied PG class, will reserve a wavelength if the number of wavelengths occupied by the PG class is less than the number of wavelengths requested by the class (i.e.,  $w_i^O < w_i^R$ ). Hence, an unsatisfied PG class  $C_i$  could reserve more wavelengths than the number of wavelengths allocated to it (i.e.,  $w_i^O > w_i^A$ ). A burst of the BE class can reserve any idle wavelength.

If contention is unavoidable, an arriving burst of a satisfied PG class can preempt a burst belonging to an unsatisfied PG class or the BE class, as long as the bursts of the satisfied PG class do not occupy the number of wavelengths allocated to the class (i.e.,  $w_i^O < w_i^A$ ) and the satisfied PG class is in danger of violating its loss threshold. If overlapping with a scheduled burst of a satisfied PG class whose loss threshold is not endangered, an arriving burst of an unsatisfied PG class can preempt the scheduled burst. Otherwise, the arriving unsatisfied PG class burst will try to preempt a burst of the BE class or a lower-priority PG class. In addition, an arriving BE class burst can preempt a burst of a satisfied PG class as long as the loss threshold of the satisfied PG class is not endangered.

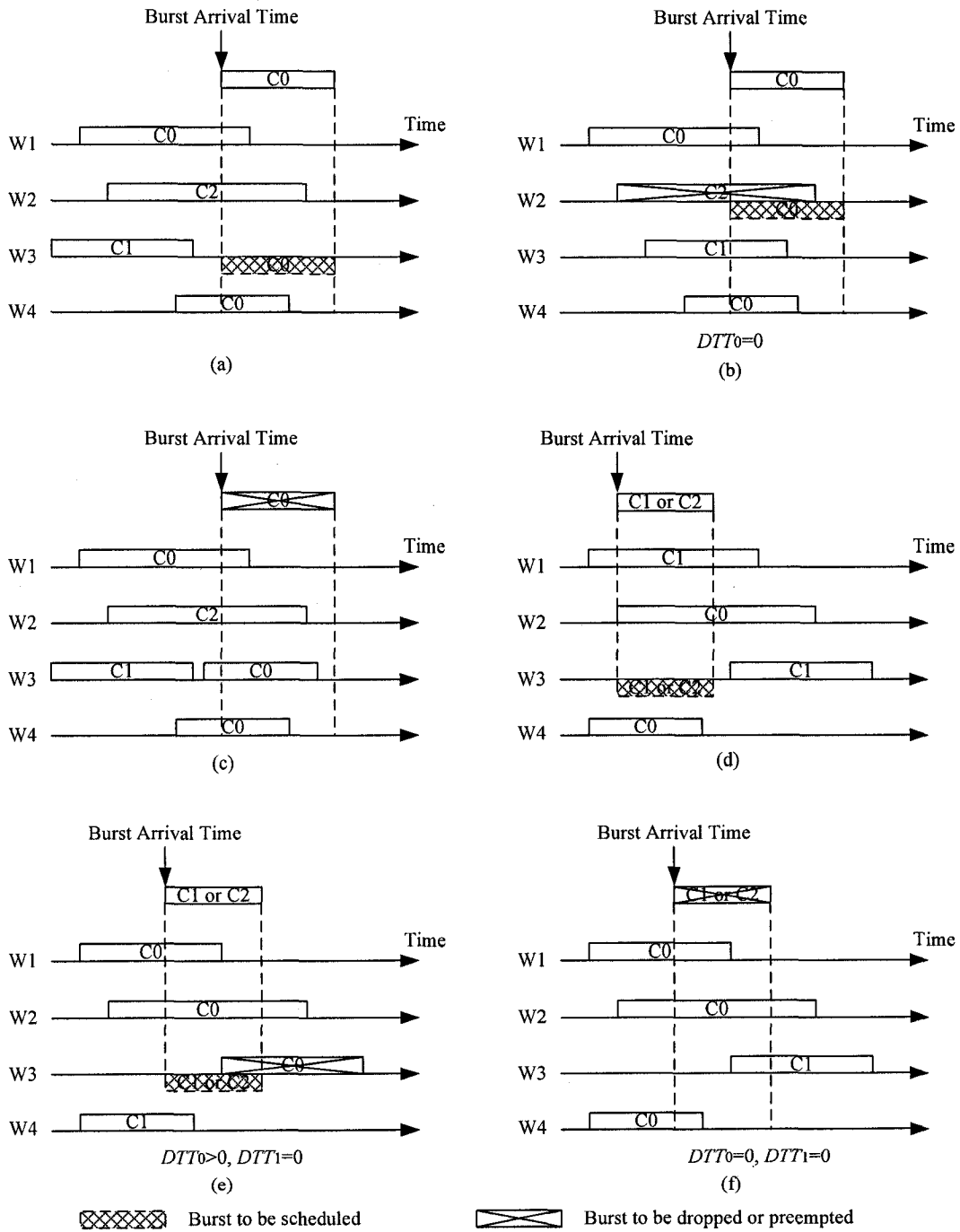


Figure 3.7 Illustration of RPS-EDWG Scheme

Figure 3.7 illustrates the scenarios when a PG burst arrives.  $C_0$  is the satisfied PG class

(i.e.,  $w_0^A = w_0^R = 3$ ),  $C_1$  is the unsatisfied PG class (i.e.,  $w_1^A < w_1^R$ ), and  $C_2$  is the BE class. In Figure 3.7(a), the arriving burst of class  $C_0$  (satisfied class) is scheduled in  $W3$ , because  $W3$  is available and  $w_0^O < w_0^A$ . In Figure 3.7(b),  $w_0^O < w_0^A$ , and the loss rate threshold of  $C_0$  is violated (i.e.,  $DTT_0 = 0$ ). Thus, the arriving  $C_0$  burst preempts the  $C_1$  burst on wavelength  $W2$ . In Figure 3.7(c), because bursts of class  $C_0$  have occupied 3 wavelengths (i.e.,  $w_0^O = w_0^A$ ), the arriving  $C_0$  burst is dropped. When the  $C_1$  or  $C_2$  burst arrives in Figure 3.7(d), there is an idle wavelength  $W3$  available, thus the arriving burst will be scheduled on  $W3$ . Here, suppose the arriving burst is of class  $C_1$ , it can still reserve  $W3$  even though  $w_1^O = w_1^A = 1$ , because class  $C_1$  is an unsatisfied PG class. In Figure 3.7(e), because all wavelengths are occupied and the class  $C_0$  is not in danger ( $DTT_0 > 0$ ), the arriving burst of the unsatisfied PG class  $C_1$  or the BE class  $C_2$  preempts the  $C_0$  burst on wavelength  $W3$ . In Figure 3.7(f), because all wavelengths are occupied and the loss threshold of class  $C_0$  is violated, the arriving burst of class  $C_1$  or  $C_2$  is dropped.

### 3.4.3 Extended RPS (ERPS) Scheme

To support a system with multiple PG classes and make sure that at least the highest-priority class can guarantee its loss rate, we have proposed some integrated schemes above. Compared to RPS-ESWG, RPS-EDWG is more flexible and can provide better performance. At the same time, RPS-EDWG allows bursts of the unsatisfied PG classes to share the spare bandwidth of the satisfied PG classes. As a result, the loss rate of the unsatisfied PG classes is reduced.

However, the integrated schemes need to allocate wavelengths on each link among different PG classes, and every node needs to keep track of the number of the wavelengths occupied by each class on every output link. Thus, they are complicated and difficult to implement. We need a simpler and easier scheme to provide performance that is not worse than what RPS-EDWG can provide.

In RPS scheme, the reason why all PG classes breaches their loss threshold under heavy traffic loads is that preemptions depend only on the DTTs of the PG classes. When the traffic load gets heavy, every PG class starts breaching its loss threshold, bursts of a higher-priority class cannot preempt bursts of a lower-priority class because the loss threshold of the lower-priority class is endangered as well. As a result, different PG classes cannot be differentiated, and all the PG classes can violate their loss thresholds at the same time under heavy traffic load.

To address this problem, we can extend the RPS scheme and let preemptions depend not only on the DTTs, but also on the priorities of the contending bursts. In other words, if contention happens between two bursts of different PG classes and both of the PG classes are violating their thresholds, we allow the higher-priority burst to preempt the lower-priority burst. As a result, the loss rate of the higher-priority class can be lowered down, and hopefully, the loss requirement of the highest-priority class can be satisfied when the traffic load is heavy.

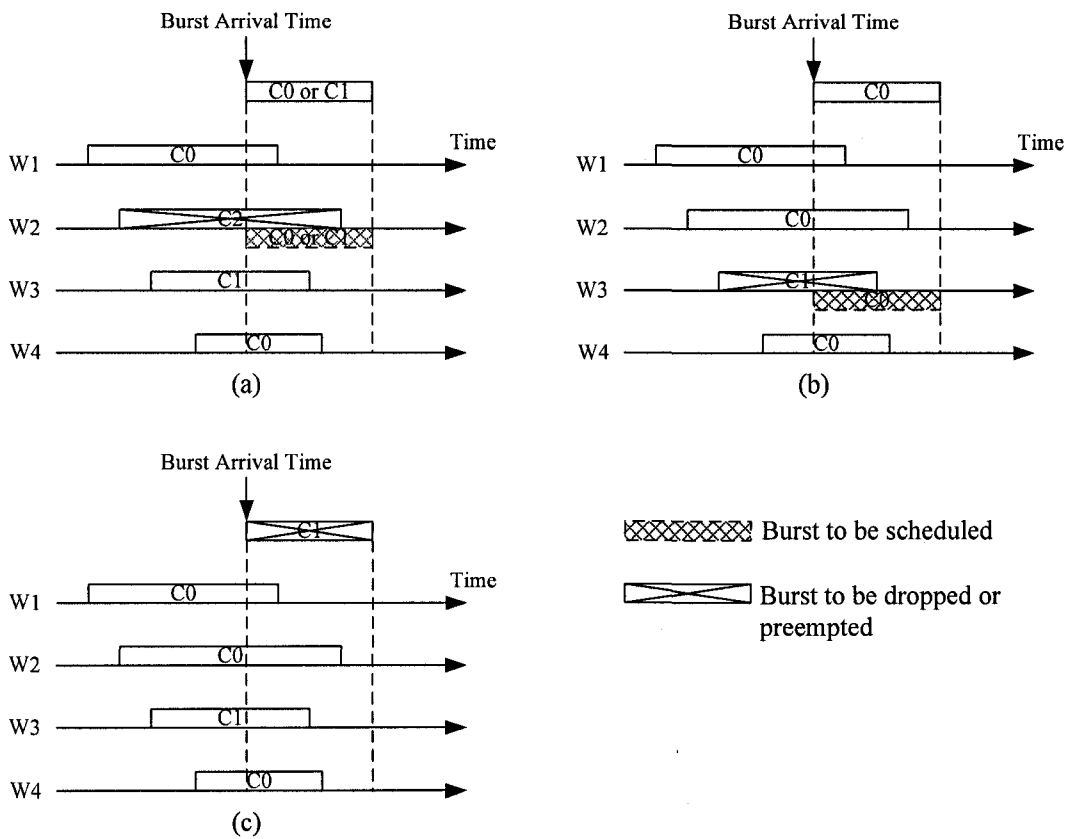


Figure 3.8 Illustration of ERPS Scheme

Figure 3.8 shows the PG class bursts arrival scenarios when the loss thresholds of both of the PG classes are violated (i.e.,  $DTT_0 = DTT_1 = 0$ ). Here,  $C_0$  and  $C_1$  are PG classes and  $C_2$  is the BE class.  $C_0$  is of the highest priority. When a scheduled burst of the BE class  $C_2$  is overlapped, it is preempted by the arriving  $C_0$  or  $C_1$  burst, as shown in Figure 3.8(a). However, as shown in Figure 3.8(b), when there are no BE bursts overlapped, the arriving burst of the higher priority class  $C_0$  preempts the overlapped burst of the lower priority class  $C_1$  even though  $DTT_1 = 0$ . In Figure 3.8(c), the arriving  $C_1$  burst cannot preempt a scheduled  $C_0$  burst and will be dropped, because  $C_0$  is of a higher priority.

The flowchart of the ERPS scheme is shown in Figure 3.9.

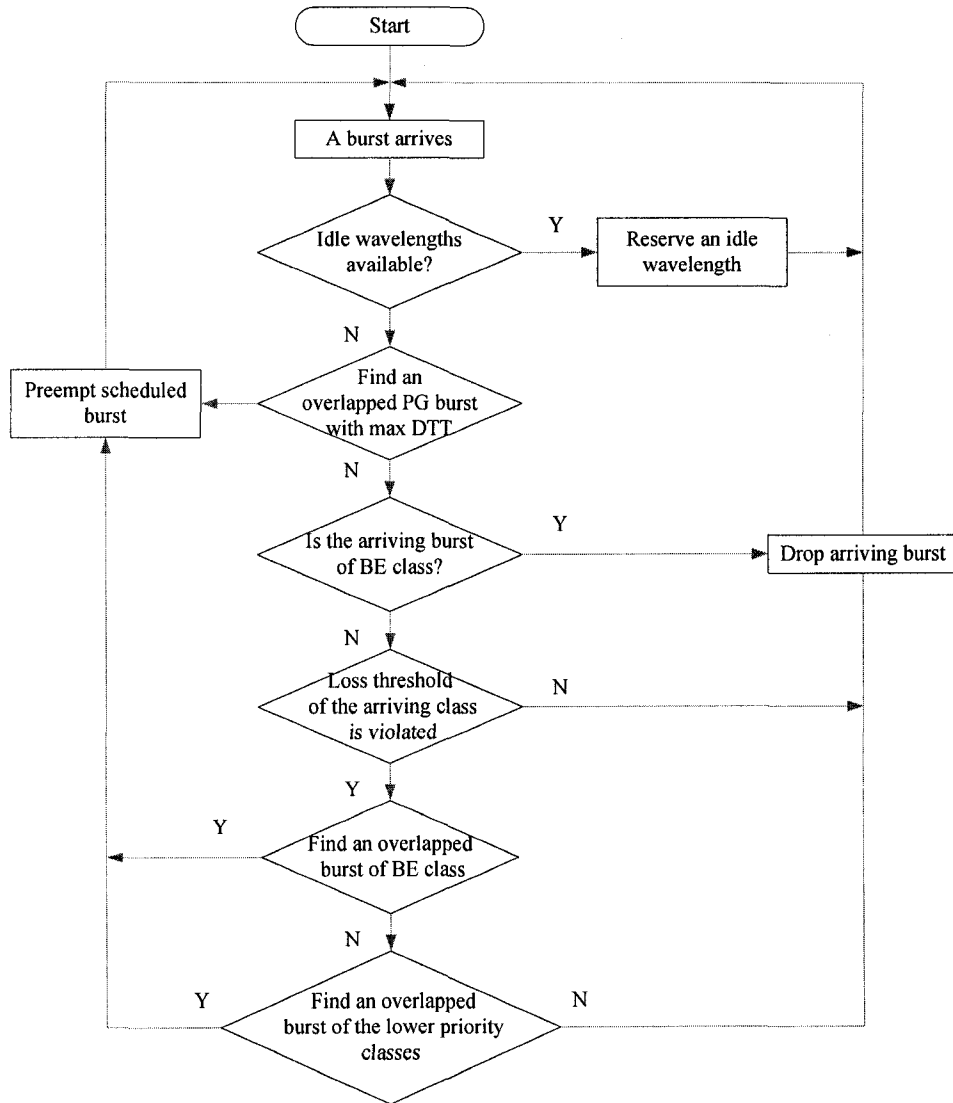


Figure 3.9 Flowchart of ERPS Scheme

### 3.5 Summary

This chapter is committed to QoS differentiation schemes on a per-hop basis. In this chapter, we have first presented the Reserve-and-Preempt Scheme (RPS), which provides the BE class

traffic with as much bandwidth as possible while guaranteeing that each of the PG classes experience a loss rate under its threshold. An analytical model has been developed based on Markov chains as well.

When the traffic load is heavy on a link in an OBS network, the limited wavelengths cannot guarantee the loss requirements of all the PG classes. In order to make sure that at least the loss rate of the highest priority class can be kept below its threshold, the RPS scheme is integrated with the wavelength grouping mechanisms, and two integrated schemes are proposed. These integrated schemes are the integrated scheme of RPS and static wavelength grouping (RPS-SWG), and the integrated scheme of RPS and dynamic wavelength grouping (RPS-DWG). To reduce the loss rates of the PG classes whose requested number of wavelengths is not satisfied, we have extended the proposed RPS-SWG and RPS-DWG schemes and presented RPS-ESWG and RPS-EDWG schemes, whereby the unsatisfied PG classes can share the wavelengths allocated to the satisfied PG classes. Although RPS-EDWG performs better than RPS-ESWG, it is complicated to implement. Therefore, we finally presented the ERPS scheme, which is simpler and easier to implement and provides the best performance.

The performance of the proposed schemes will be demonstrated in Chapter 5 by simulations. The analytical model of the RPS scheme will be validated in Chapter 5 as well.

In the next chapter, we will apply the proposed ERPS scheme over an entire network to satisfy the E2E loss requirements of different PG classes while minimizing the performance penalty that the BE class suffers from.

# Chapter 4

## End-to-End Absolute QoS Differentiation

### 4.1 Introduction

In Chapter 3, we have first introduced the Reserve-and-Preempt Scheme (RPS), which is a per-hop absolute QoS differentiation scheme in OBS networks. Then, we have presented a variety of QoS differentiation schemes that have been extended from the RPS scheme. Among the proposed schemes, the ERPS scheme is easy to implement and outperforms the other schemes. However, our ultimate objective in this thesis is to provide an absolute QoS differentiation on an E2E basis. In this chapter, to guarantee the E2E loss requirements of the PG classes while successfully delivering as many BE bursts as possible, we apply the ERPS scheme over an entire network.

In this chapter, we first introduce the system architecture and the problem formulations.

After that, we propose two optimized priority-grouping techniques: *optimized priority-grouping with single-class constraint (OPT-SC)* and *optimized priority-grouping without single-class constraint (OPT-NC)*. Then, we introduce the mechanism to label a burst at each node along its path from the source to the destination. To cope with the traffic-fluctuation and the load-unbalance problems, two priority-level adjustment mechanisms, *priority-level upgrading (PLU)* and *priority-level degrading (PLD)*, are also presented. Finally, the two mechanisms are combined into an *integrated self-adaptive algorithm* in order to provide better performance in the network.

## 4.2 System Architecture

In an OBS network, packets are assembled into bursts at the ingress nodes and each of the bursts is transmitted through the core nodes along its path to the egress node, where the burst is disassembled into data packets that are delivered to the corresponding clients.

First, we define the term “flow” as traffic of a specific class along a specific path between a source-destination pair. Suppose a flow ( $f_{i,sd}$ ) of class  $C_i$  passes through a path of  $h$  hops from source node  $s$  to destination node  $d$ . At intermediate node  $k$  ( $k=1, \dots, h$ ), the flow experiences a loss rate  $p_{C_i,sd}^k$ , which is lower than its per-hop loss threshold  $\overline{p_{C_i,sd}^k}$ . Therefore, the E2E loss rate of the flow is  $P_{C_i,sd}^{e2e}$ :

$$P_{C_i,sd}^{e2e} = 1 - \prod_{k=1}^h (1 - p_{C_i,sd}^k) \leq 1 - \prod_{k=1}^h (1 - \overline{p_{C_i,sd}^k}). \quad (4.1)$$

Let  $p_{C_i, sd}^{\max}$  be the maximum per-hop loss threshold of the flow on the intermediate links along its path, i.e.,

$$p_{C_i, sd}^{\max} = \max_{k=1}^h \overline{p_{C_i, sd}^k}. \quad (4.2)$$

Thus, we have:

$$P_{C_i, sd}^{e2e} \leq 1 - (1 - p_{C_i, sd}^{\max})^h \quad (4.3)$$

Suppose the per-hop loss threshold  $\overline{p_{C_i, sd}}$  on every intermediate node is equal to  $p_{C_i, sd}^{\max}$ , which can be satisfied on a link with the heaviest traffic load along the path:

$$\overline{p_{C_i, sd}} = p_{C_i, sd}^{\max}. \quad (4.4)$$

To guarantee that the E2E loss rate ( $P_{C_i, sd}^{e2e}$ ) is lower than the E2E loss threshold ( $\overline{P_{C_i}^{e2e}}$ ) of class  $C_i$ , we assume the per-hop loss threshold  $\overline{p_{C_i, sd}}$  on the intermediate nodes satisfy:

$$\overline{P_{C_i}^{e2e}} = 1 - (1 - \overline{p_{C_i, sd}})^h. \quad (4.5)$$

The above equation can be rearranged as:

$$\overline{p_{C_i, sd}} = 1 - e^{\ln(1 - \overline{P_{C_i}^{e2e}})/h}. \quad (4.6)$$

Therefore, from the E2E loss rate threshold  $\overline{P_{C_i}^{e2e}}$ , we can obtain a universal per-hop loss

threshold  $\overline{p_{C_i,sd}}$ . As long as the per-hop loss rate can be kept below the per-hop loss threshold on every intermediate node along the path (i.e.,  $p_{C_i,sd}^k \leq \overline{p_{C_i,sd}}, 1 \leq k \leq h$ ), the E2E loss threshold  $\overline{P_{C_i}^{e2e}}$  can be guaranteed.

In this chapter, we apply the ERPS scheme on every link to guarantee that the per-hop loss rate of every flow is kept below its per-hop loss threshold, which is calculated from (4.6) based on its E2E loss threshold.

### 4.3 Setting Per-hop Loss Thresholds on Links

To implement E2E absolute QoS differentiation for flow  $f_{i,sd}$  in an OBS network, the first task is to set the per-hop loss thresholds on every link along its path. In the network, every link could be shared by multiple paths passing through different hop-distances. Different flows share the same E2E loss threshold  $\overline{P_{C_i}^{e2e}}$  as long as they are of the same class  $C_i$ . However, according to (4.6), flows passing through different hop-distances may have different per-hop loss threshold ( $\overline{p_{C_i,sd}}$ ) even if they are of the same service class. On the contrary, flows that pass through different paths with the same hop-distances  $h$  share the same per-hop loss threshold  $\overline{p_{C_i,h}}$ :

$$\overline{p_{C_i,sd}} = \overline{p_{C_i,h}}, \text{ if } D_{sd} = h, \quad (4.7)$$

where  $D_{sd}$  is the hop-distance between source node  $s$  and destination node  $d$ . On a per-hop

basis, we define flows with the same class  $C_i$  and the same hop-distance  $h$  as a “flow-priority-bundle” (FPB)  $L_{C_i,h}$ . On an intermediate link, an FPB is a group of flows that are of the same class and pass through the same hop-distance. The flows in an FPB must have different paths and share the same intermediate link. The flows of the same class could belong to different FPBs if they have different hop-distances.

To set the per-hop loss thresholds on the intermediate links, the most natural approach is to treat each FPB separately. We call this *FPB-oriented approach*. Suppose a link is shared by paths of different hop-distances, then, flows with different classes or different hop-distances (i.e., different FPBs) have different per-hop loss thresholds on a link:

$$\overline{p_{C_i,h_1}} \neq \overline{p_{C_j,h_2}}, \text{ if } C_i \neq C_j \text{ or } h_1 \neq h_2. \quad (4.8)$$

Hence, if the maximum hop-distance of the sharing paths on link  $l_{m,n}$  is  $H_{m,n}$ , there could be  $H_{m,n}$  different FPBs for the same service class on the link. Suppose there are  $N$  classes including the BE class, the system needs to handle up to  $H_{m,n} * (N-1) + 1$  different FPBs on the link. This approach provides the optimal performance because the per-hop loss threshold that is calculated from (4.6) is the exact per-hop loss threshold required to guarantee the E2E loss rate of the flow. Thus, as long as their per-hop loss requirements can be satisfied on every link, flows of the PG classes can have their E2E loss requirements guaranteed, and the BE class traffic can be provided with the maximum spare bandwidth. However, the drawback of this approach is the scalability problem. In a big network supporting multiple service classes, every link needs to support a large number of different

FPBs.

To the other extreme, in order to solve the scalability problem in the FPB-oriented approach, we can set a common loss threshold for every service class on a link. We call this approach *class-oriented approach*. In other words, we assign all the flows of the same class to the same priority-group and give every group a per-hop loss threshold  $\overline{p_{C_i}}$ , which is shared by all the flows in the group even if they have different hop-distances. The per-hop loss threshold  $\overline{p_{C_i}}$  of service class  $C_i$  on the link is set as the minimum of the per-hop loss thresholds of class  $C_i$  flows on the link, and it equals the per-hop loss threshold of the class  $C_i$  flow with the maximum hop-distance  $H_{m,n}$ :

$$\overline{p_{C_i}} = \min_{h=1}^{H_{m,n}} \{ \overline{p_{C_i,h}} \} = \overline{p_{C_i,H_{m,n}}} \quad (4.9)$$

Now we suppose there are  $N$  service classes in the system. With this approach, each link needs to support only  $N$  priorities. Hence, it is scalable and easy to implement. However, a class  $C_i$  flow with a shorter hop-distance  $h$  will experience an E2E loss rate much lower than its E2E loss threshold  $\overline{P_{C_i}^{e2e}}$  because the per-hop loss threshold ( $\overline{p_{C_i}}$ ) is lower than the per-hop loss threshold of the flow ( $\overline{p_{C_i,h}}$ ), which is calculated from (4.6) on each intermediate link:

$$\overline{p_{C_i}} = \overline{p_{C_i,H_{m,n}}} < \overline{p_{C_i,h}}, \text{ if } h < H_{m,n}. \quad (4.10)$$

The unnecessarily low loss rates experienced by the flows passing through shorter hop-distances lead to *unnecessary bandwidth consumption* problem. Further, the unnecessary

bandwidth consumption problem results in higher loss rates of BE class flows, which is not desirable.

Therefore, we need an approach to achieve a balance between scalability and unnecessary bandwidth consumption on every link. On each link, we can cluster FPBs into a limited number of priority-groups and the elements in each of the groups share a common per-hop loss threshold on the link. We call this *priority-grouping approach*. In this approach, all the flow elements in a priority-group  $G_a$  share a common per-hop loss threshold  $\overline{p}_{G_a}$ :

$$\overline{p}_{G_a} = \min_{\{\forall (i,h) | L_{C_i,h} \in G_a\}} \{\overline{p}_{C_i,h}\} , \quad (4.11)$$

where  $L_{C_i,h}$  is the FPB of the class  $C_i$  flows with hop-distance of  $h$ . However, this method cannot totally avoid the unnecessary bandwidth consumption problem. All we can do is to do our best to alleviate its effect.

To group the flows on a link, there are two questions:

1. How many priority-groups are there on a link?
2. What is the group combination on each link? In other words, to which group does each FPB belong?

The priority-group number on a link depends on how many priorities the network can support. We only consider the second question here.

In [ZHA04a], a *fixed priority-grouping (FPG) approach* was proposed. Each

priority-group is composed of flows of the same class. Different flows of the same class could be clustered into different priority-groups based on the hop-distances of their paths. In this approach, the same priority-group combination is shared by all the links in the network. The flow with a specific service class and a specific hop-distance is assigned to the same priority-group on every intermediate link along its path, no matter how many paths share the link, and no matter what the traffic load is.

In a network, suppose there are two classes:  $C_0$  is the PG class and  $C_1$  is the BE class. The maximum hop-distance of all the paths is 6, and the network supports 3 priority-levels. We let  $C_0$  flows with hop-distances of 4, 5 and 6 in group  $G_0$  ( $G_0 = \{f_{C_0,4}, f_{C_0,5}, f_{C_0,6}\}$ ),  $C_0$  flows with hop-distances of 1, 2 and 3 in another group  $G_1$  ( $G_1 = \{f_{C_0,1}, f_{C_0,2}, f_{C_0,3}\}$ ), and the BE class flows in the third group  $G_2$  ( $G_2 = \{f_{C_1,1}, f_{C_1,2}, f_{C_1,3}, f_{C_1,4}, f_{C_1,5}, f_{C_1,6}\}$ ). According to (4.11), the per-hop loss thresholds of the first two groups are set as  $\overline{p_{G_0}} = \overline{p_{C_0,6}}$  and  $\overline{p_{G_1}} = \overline{p_{C_0,3}}$  respectively. This approach arbitrarily clusters the flows on every link.

However, in a network, traffic load distribution of different hop-distances is not always symmetric on every link. Let us consider the scenario that a link is shared by paths whose hop-distances are only 1 or 4. The first two priority-groups expect per-hop loss thresholds of  $\overline{p_{C_0,1}}$  and  $\overline{p_{C_0,4}}$  respectively. However, their per-hop loss thresholds are set as  $\overline{p_{C_0,3}}$  and  $\overline{p_{C_0,6}}$  respectively. Because  $\overline{p_{C_0,1}} > \overline{p_{C_0,3}}$  and  $\overline{p_{C_0,4}} > \overline{p_{C_0,6}}$ , all the flows of the two priority-groups will experience unnecessarily low loss rates, which result in unnecessary

bandwidth consumption problem that is supposed to be alleviated further.

To reduce unnecessary bandwidth consumption, we develop two optimized priority-grouping (OPG) approaches here.

### 4.3.1 Optimized Priority-grouping Approach with Single-Class Constraint (OPG-SC)

To make the priority-grouping easier to implement, this approach makes a constraint as the class-oriented approach does: all elements in a priority-group must belong to the same class. We call this single-class constraint (SC). However, in this approach, different links do not share the same priority-group combination any more. Along its path, a flow could be assigned to different priority-groups on different links, not only depending on the hop-distance of the flow, but also depending on the traffic load distribution on the links. Therefore, along a path, different links can have different priority-group combinations. We assume the flows of each class can be assigned to  $u$  priority-groups on a link. Suppose there are  $N$  classes, among which class  $C_0$  to class  $C_{N-2}$  are PG classes and class  $C_{N-1}$  is the BE class. Therefore, there are  $u \cdot (N - 1) + 1$  groups in total. The flows of class  $C_i$  are assigned to priority-groups from  $G_{u \cdot i}$  to  $G_{u \cdot (i+1) - 1}$ . The flows of the BE class are all assigned to the priority-group  $G_{u \cdot (N-1)}$ .

To make the group combinations optimized, *i.e.*, to reduce unnecessary bandwidth consumptions while guaranteeing the E2E loss thresholds of the PG class flows, we need to assign every flow to a priority-group whose loss threshold satisfies the following conditions:

1. To guarantee the E2E loss thresholds, the per-hop loss threshold of a priority-group cannot be greater than the per-hop loss thresholds of each of the elements. For example, if FPB  $L_{C_i,h}$  is assigned to group  $G_a$ , the following condition needs to be satisfied:

$$\overline{p_{G_a}} \leq \overline{p_{C_i,h}}, \quad \text{if } L_{C_i,h} \in G_a \quad . \quad (4.12)$$

2. To alleviate the unnecessary bandwidth consumption problem, the loss threshold of a group  $G_a$  must be the closest to the per-hop loss threshold of each of the elements:

$$\overline{p_{C_i,h}} - \overline{p_{G_a}} = \min_{\{\forall j | p_{C_i,h} \geq p_{G_j}\}} \{\overline{p_{C_i,h}} - \overline{p_{G_j}}\} \quad . \quad (4.13)$$

3. In addition, the loss threshold of a priority-group should be set as the minimum of the per-hop loss thresholds of its elements, as shown in (4.11).

Therefore, on each intermediate link, we need to sort the per-hop loss thresholds of the flows into a descending sequence for each class, and then, break the sorted sequence into a limited number of segments, each of which corresponds to a priority-group. From (4.6), we know that for the same class, flows with a shorter hop-distance can tolerance a greater per-hop loss threshold. This can be expressed as:

$$p_{C_i,h_1} > p_{C_i,h_2}, \quad \text{if } h_1 < h_2 \quad . \quad (4.14)$$

Hence, we can just sort the per-hop loss thresholds of the flows based on their hop-distances as shown in Figure 4.1.

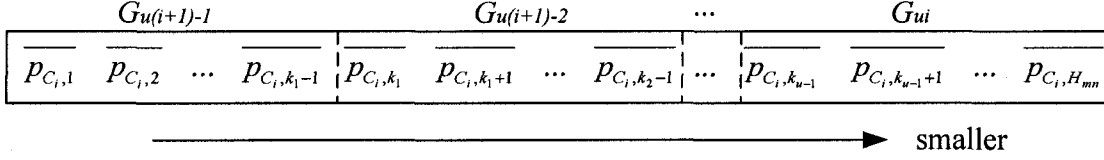


Figure 4.1 Sorted Per-hop Loss Thresholds of OG-SC on a Link

As Figure 4.1 shows, suppose there are  $N$  classes in the network. On link  $l_{m,n}$ , the maximum hop-distance of the sharing paths is  $H_{m,n}$ , and the flows of every PG class can be clustered into  $u$  groups. The flows of service class  $C_i$  with hop-distances from 1 to  $k_1 - 1$  are clustered into group  $G_{u(i+1)-1}$ , the flows of service class  $C_i$  with hop-distances from  $k_1$  to  $k_2 - 1$  are in group  $G_{u(i+1)-2}$ , and so on. Here the priority level of the group  $G_{u(i+1)-1}$  is lower than that of the group  $G_{u(i+1)-2}$ . The loss threshold of the group should be the minimum of the per-hop thresholds of the elements in the group:

$$\begin{aligned}
 \overline{p_{G_{u(i+1)-1}}} &= \min_{h=1}^{k_1-1} \{ \overline{p_{C_i,h}} \} = \overline{p_{C_i,k_1-1}} \\
 \overline{p_{G_{u(i+1)-(j+1)}}} &= \min_{h=k_j}^{k_{j+1}-1} \{ \overline{p_{C_i,h}} \} = \overline{p_{C_i,k_{j+1}-1}} \quad (0 < j < u-1). \\
 \overline{p_{G_{ui}}} &= \min_{h=k_{u-1}}^{H_{mn}} \{ \overline{p_{C_i,h}} \} = \overline{p_{C_i,H_{mn}}}
 \end{aligned} \tag{4.15}$$

To reduce unnecessary bandwidth consumption, we need to find an optimized group combination that minimizes the unnecessary bandwidth consumption:

$$\sum_{h=1}^{k_1-1} (\overline{p_{C_i,h}} - \overline{p_{G_{u(i+1)-1}}}) \lambda_{C_i,h} + \sum_{j=1}^{u-1} \sum_{h=k_j}^{k_{j+1}-1} (\overline{p_{C_i,h}} - \overline{p_{G_{u(i+1)-(j+1)}}}) \lambda_{C_i,h} + \sum_{h=k_{u-1}}^{H_{mn}} (\overline{p_{C_i,h}} - \overline{p_{G_{ui}}}) \lambda_{C_i,h} \tag{4.16}$$

Or,

$$\sum_{h=1}^{k_1-1} (\overline{p_{C_i,h}} - \overline{p_{C_i,k_1-1}}) \lambda_{C_i,h} + \sum_{j=1}^{u-1} \sum_{h=k_j}^{k_{j+1}-1} (\overline{p_{C_i,h}} - \overline{p_{C_i,k_{j+1}-1}}) \lambda_{C_i,h} + \sum_{h=k_{u-1}}^{H_{mn}} (\overline{p_{C_i,h}} - \overline{p_{C_i,H_{mn}}}) \lambda_{C_i,h} \quad (4.17)$$

So, for service class  $C_i$ , we need to find the optimized breakpoints  $k_1, k_2, \dots, k_{u-1}$ , which break the sorted descending sequence  $(\overline{p_{C_i,1}}, \overline{p_{C_i,2}}, \dots, \overline{p_{C_i,H_{mn}}})$  into  $u$  groups. This is a discrete linear programming problem:

Variables:

$$k_1, k_2, \dots, k_{u-1}$$

Objective:

$$\text{Minimize } \sum_{h=1}^{k_1-1} (\overline{p_{C_i,h}} - \overline{p_{C_i,k_1-1}}) \lambda_{C_i,h} + \sum_{j=1}^{u-1} \sum_{h=k_j}^{k_{j+1}-1} (\overline{p_{C_i,h}} - \overline{p_{C_i,k_{j+1}-1}}) \lambda_{C_i,h} + \sum_{h=k_{u-1}}^{H_{mn}} (\overline{p_{C_i,h}} - \overline{p_{C_i,H_{mn}}}) \lambda_{C_i,h} \quad (4.18)$$

Constraints:

$$\begin{aligned} 0 < k_1 &\leq H_{mn} - (u - 2) \\ k_{i-1} < k_i &\leq H_{mn} - (u - 1 - i) \\ k_{u-2} < k_{u-1} &\leq H_{mn} \end{aligned} \quad (4.19)$$

Solving the optimal problem for each service class, we can obtain an optimized group combination, which can make sure that the unnecessary bandwidth consumption can be minimized under the single-class constraint.

### 4.3.2 Optimized Priority-grouping without Single-Class Constraint (OPG-NC)

In the above approach, flows are grouped within a class according to their per-hop loss thresholds. With OPG-SC, flows belonging to a higher-priority class will definitely be assigned to a higher priority-group. However, in a system with multiple PG classes, the per-hop loss threshold of a flow belonging to a lower-priority class with longer hop-distance could be smaller than that belonging to a higher-priority class with shorter hop-distance. In this case, assigning the flows of the higher-priority class with shorter hop-distance to a higher-priority group leads to unnecessary bandwidth consumption. Therefore, the priority-group combinations given by this approach may not be the optimal one in a system supporting multiple PG classes. Let us suppose there are two PG classes ( $C_0$  and  $C_1$ ) in a network, and  $\overline{p_{G_1}} < \overline{p_{G_2}} \leq \overline{p_{C_{1,6}}} < \overline{p_{C_{0,1}}}$  on a link. With the single-class constraint, FPB  $L_{C_{0,1}}$  is assigned to the higher priority-group  $G_1$  and  $L_{C_{1,6}}$  is assigned to the lower priority-group  $G_2$ . As we mentioned before, to alleviate unnecessary bandwidth consumption problem, a flow need to be assigned to a priority-group whose per-hop loss threshold is the closest to the per-hop loss threshold of the flow. However, with OPT-SC,  $L_{C_{0,1}}$  is assigned to  $G_1$ , whose loss threshold is not as close to the per-hop loss threshold of  $L_{C_{0,1}}$  as the loss threshold of  $G_2$  (i.e.  $\overline{p_{C_{0,1}}} - \overline{p_{G_1}} > \overline{p_{C_{0,1}}} - \overline{p_{G_2}}$ ). Thus, the flows in  $L_{C_{0,1}}$  will expect a lower loss threshold of  $\overline{p_{G_1}}$ , instead of a higher loss threshold  $\overline{p_{G_2}}$ .

Therefore, we can relax the single-class constraint. That means, flows of different classes are allowed to be clustered into the same priority-group. First, we need to calculate the per-hop loss threshold for each element from (4.6). If there are  $N-1$  PG classes and the maximum hop-distance on link  $l_{m,n}$  is  $H_{m,n}$ , there are  $(N-1) \cdot H_{m,n}$  different per-hop loss thresholds. Then, we need to sort the per-hop loss thresholds to an ascending sequence  $(p_0, p_1, \dots, p_{(N-1) \cdot H_{m,n}-1})$  as Figure 4.2 shows. In Figure 4.2, each of the elements in the sorted sequence corresponds to a per-hop loss threshold, i.e.,  $\forall 0 \leq j \leq (N-1) \cdot H_{m,n} - 1$ ,  $\exists 0 \leq i \leq N-1, 1 \leq h \leq H_{m,n}, p_j = \overline{p_{C_i,h}}$ .

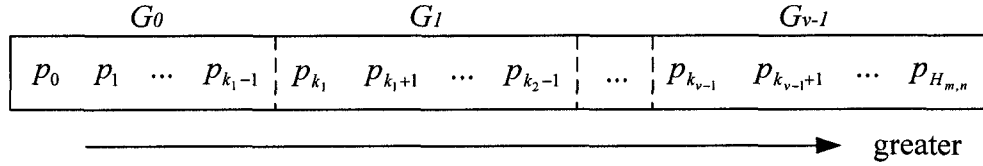


Figure 4.2 Sorted Per-hop Loss Thresholds of OG-NC on a Link

Suppose the system can support  $v$  priorities, not including the BE class. We need to break the sorted sequence into  $v$  segments, each of which belongs to a priority-group. Now, the question is how to segment the sorted sequence. To get an optimized group combination,  $v-1$  optimized breakpoints  $(k_1, k_2, \dots, k_{v-1})$  need to be found. Therefore, we have the following problem to solve:

Variables:

$$k_1, k_2, \dots, k_{v-1};$$

Objective:

Minimize unnecessary bandwidth consumption

$$\text{Minimize } \sum_{j=0}^{k_1-1} (p_j - p_0) \lambda_{C_i,h} + \sum_{j=k_1}^{k_2-1} (p_j - p_{k_1}) \lambda_{C_i,h} + \dots + \sum_{j=k_{v-1}}^{(N-1)H_{mn}-1} (p_j - p_{k_{v-1}}) \lambda_{C_i,h} \quad (4.20)$$

Constraints:

$$\begin{aligned} 0 < k_1 &\leq (N-1)H_{mn} - v \\ k_{i-1} < k_i &\leq (N-1)H_{mn} - (v-i), \quad 1 < i \leq v-1, \quad \forall j, \exists i, h, p_j = \overline{p_{C_i,h}} \\ k_{v-2} < k_{v-1} &\leq (N-1)H_{mn} - 1 \end{aligned} \quad (4.21)$$

Solving the above discrete optimal problem, we can get the optimized group combination, in which each group can be composed of elements of different classes. With the single service class constraint removed, this OPG-NC approach outperforms the OPG-SC approach in terms of unnecessary bandwidth consumption.

## 4.4 Labeling Arrival Bursts

To apply ERPS scheme after the flows have been clustered into different priority-groups on every link, each arriving burst need to be labeled with the ID of the priority-group it belongs to. Suppose a network supports  $v$  priority-groups on a link, each of which is identified by a particular label. In the network, every intermediate node maintains a table for each of the output links. Once the optimized group combination is calculated on a link, the table of the link is constructed as well. Assume there are  $N$  classes in the system and the maximum

hop-distance of the paths passing through the link is  $H$ , the table for the link has  $N \cdot H$  tuples, and each tuple has three attributes: service class, hop-distance, and label. Different labels correspond to different priority-groups.

In the network, the arriving bursts need to be labeled as different priority-groups. When the BHP of a burst arrives at a node, the node first extracts information of the output link, the service class and the hop-distance of the burst, then queries the table of the output link for its label based on the service class and the hop-distance. Finally, the node tries to schedule the burst based on the label (i.e., its priority-group) using the ERPS scheme. (Note that in Chapter 3, the ERPS scheme schedules bursts based on their classes.) If the burst is scheduled successfully, the node will keep its label as well as its start time, end time and ID on the link, in order to determine whether the burst needs to be preempted when another arriving burst overlaps with it later. For example, the BHP of a burst of service class  $C_0$  arrives at intermediate node 3, its hop-distance from the source to the destination is 4, and the next node it is heading for is node 8. When the BHP of the burst arrives at the intermediate node 3, the node first extracts the output link  $l_{3,8}$  from the control packet, and then checks the table of the link  $l_{3,8}$ . According to the service class and the hop-distance information extracted from the control packet, a label can be obtained from the table. Based on the label, the arriving burst could reserve bandwidth, preempt a scheduled burst or be dropped according to the ERPS scheme we have presented in Chapter 3. What we need to point out here is that along the path of the burst, it could have different labels on different links, because a priority-group combination is not shared among all the links in the network. Therefore, the label of the burst

needs to be swapped at the intermediate nodes.

## 4.5 Self-Adaptive Algorithm

The optimized priority-grouping approaches assume that every link along the path of a flow is in “*uncritical situation*”, i.e., the per-hop loss threshold on every intermediate link of the flow can be satisfied. For the flow, as long as the per-hop loss threshold of its priority-group is not violated on every intermediate link, the E2E loss rate can be guaranteed.

However, this assumption does not reflect the nature of a real network. First, in a real network, the traffic load changes from time to time. Second, usually the traffic load is not balanced on the links along a path in the network. In other words, while the bottleneck links are in critical situation, the other links can be in uncritical situation.

When the traffic load gets heavy on a bottleneck link, the loss rate of a flow can exceed the per-hop loss threshold of the priority-group that the flow belongs to, or even exceed the per-hop loss threshold of the flow. As a result, its E2E loss threshold could be violated, and the flow is called *unsatisfied flow*.

On the other hand, sometimes the traffic load gets lighter after the flow has been assigned to a relatively higher priority-group just in order to guarantee its E2E loss threshold. Of course, its E2E loss threshold can still be satisfied under the lighter traffic load. However, the higher priority-group makes the E2E loss rate of the flow unnecessarily low and leads to unnecessary bandwidth consumption problem.

While trying to save bandwidth for BE class flows, our first goal is to make sure that flows of the PG classes could be satisfied of their E2E loss thresholds. When the traffic load is heavy in a network, it is impossible for every flow to be guaranteed of its E2E loss threshold. In this case, we need a mechanism to reduce the number of the unsatisfied flows whose E2E loss thresholds are violated. On the other hand, the other goal is to deliver as many BE class bursts as possible over the network. When the traffic load is light, we need a mechanism to reduce the unnecessary bandwidth consumptions, and therefore, save more bandwidth for the unsatisfied PG flows and the BE class flows.

To meet the above requirements, a self-adaptive algorithm is needed to have every core node adjust the priority-group combinations on its output links according to the traffic loads of the sharing flows.

How does the self-adaptive algorithm work to handle the traffic-fluctuation and the load-unbalance problems in order to reduce the number of unsatisfied flows while alleviating the unnecessary bandwidth consumption problem? The self-adaptive algorithm should include two mechanisms: priority-level upgrading (PLU) mechanism and priority-level degrading (PLD) mechanism. Periodically, the system monitors the E2E loss rate of every flow, and the per-hop loss rate of each priority-group is monitored on every link as well. The PLU mechanism and the PLD mechanism, respectively, upgrade the priority-levels of the unsatisfied flows and degrade the priority-levels of the satisfied flows on each link along their paths at the end of each time-cycle. Hence, the E2E loss rates of the unsatisfied flows are lowered down, and some of them become satisfied. At the same time, the loss rates of the

satisfied flows increase towards their thresholds. As a result, the unnecessary bandwidth consumed by the satisfied flow can be reduced, and the saved bandwidth can be utilized by the BE class traffic.

### 4.5.1 Priority-Level Upgrading (PLU) Mechanism

When the traffic load is heavy in a network, the per-hop loss thresholds of some or all of the priority-groups in a bottleneck link could be violated. We say the link is a *critical link* to the priority-groups and their element flows. On the contrary, if the per-hop loss rate of a flow is lower than the per-hop loss threshold of its priority-group on a link, the link is an *uncritical link* to the flow. If one or more of its intermediate links are critical to a flow, the E2E loss threshold of the flow could be violated even if the other intermediate links are uncritical to the flow.

In a network, the end users do not care about what the overall loss rates are. Instead, what they are concerned about is if their applications can be satisfied of their loss requirements. Hence, we need to try our best to make as many flows as possible become satisfied, and the E2E loss rate of every unsatisfied flow needs to be lowered down towards its E2E loss threshold. In this case, the E2E loss rate of an unsatisfied flow can be reduced by upgrading its priority-levels on the links along its path, because flows in a higher priority-group experience lower loss rate.

To implement the PLU mechanism on an unsatisfied flow, first, every intermediate link along the path needs to be searched for an eligible higher priority-group. After that, the tables

on the links are updated in order to assign the flow to the eligible higher priority-group.

Suppose flow  $f_{C_i,sd}$  is an unsatisfied flow. The hop-distance from the source node  $s$  to the destination node  $d$  is  $h$ . We want the E2E loss rate of the flow to be made lower than its E2E loss threshold  $\overline{P_{C_i}^{e2e}}$  by upgrading its priority-levels on as few links as possible. Hence, we start from finding the link where the flow suffers from the maximum per-hop loss rate among all the links along its path.

To reduce the E2E loss rate of the flow, the candidate priority-groups on an intermediate link must be of higher priorities than the current priority-group of the flow. The loss threshold of the eligible priority-group  $G_{j'}$  must be lower than that of the current priority-group  $G_j$  (i.e.,  $\overline{P_{G_{j'}}} < \overline{P_{G_j}}$ ). In an OPG-NC-based network, suppose an unsatisfied flow  $f_{C_i,sd}$  is currently of priority-group  $G_j$  on link  $l_{m,n}$ , the candidate priority-groups are from  $G_{j-1}$  to  $G_0$ . On the other hand, in an OPG-SC-based network, the candidate priority-groups are only the priority-groups belonging to the service class of the unsatisfied flow. Without loss of generality, in the following sections, we only consider networks with OPG-NC scheme.

To implement the PLU mechanism, candidate priority-group  $G_{j'}$  needs to be experiencing a loss rate that is lower than its own loss threshold ( $P_{G_{j'}} < \overline{P_{G_{j'}}}$ ), i.e., there is room to accommodate the flow  $f_{C_i,sd}$  in the priority-group. Otherwise, the performance of the flows belonging to the priority-group would be deteriorated further after the new flow is added into the priority-group. To lessen the probability that the loss rate of a priority-group

exceeds its threshold after a flow is switched to the priority-group, we set a *load-increase safety constant*  $\varepsilon$ . Thus, a candidate priority-group  $G_{j'}$  must satisfy:

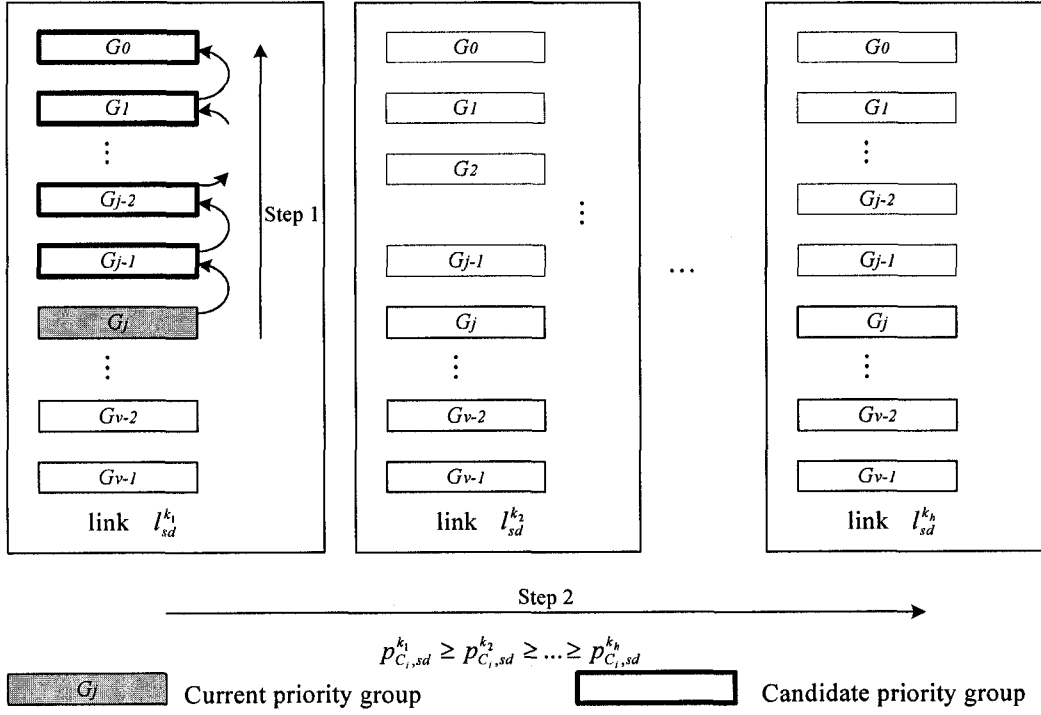
$$p_{G_{j'}} < \varepsilon \cdot \overline{p_{G_{j'}}}, \quad 0 < \varepsilon < 1 \quad (4.22)$$

Moreover, no other flows are supposed to be added to a priority-group  $G_{j'}$  before the new flow is added in the same time-cycle. If multiple flows are added to the same priority-group in the same time-cycle, it will be more likely that the loss threshold of the priority-group ( $\overline{p_{G_{j'}}$ ) be endangered. To avoid this case, whenever a flow is added to a priority-group, we set a flag for the priority-group on the link. We use  $j'$  to keep the label of the new priority-group. If an eligible priority-group is found on the link,  $j'$  is set as the label of the group. Otherwise,  $j' = j$ , where  $j$  is the label of the original priority-group. After the higher priority-level searching procedure, the flow is switched to the new priority-group  $G_{j'}$ .

Figure 4.3 shows the priority-level upgrading procedure in a network with the OPG-NC scheme, we start searching for an eligible higher priority-group from the link where the flow suffers from the maximum loss rate. Sometimes, no candidate priority-groups are available on that link (i.e. (4.22) cannot be satisfied). Or, updating the priority-level of the flow on the link does not make the expected E2E loss rate ( $P_{C_i, sd}^{e2e}$ ) of the flow below its E2E loss threshold  $\overline{P_{C_i}^{e2e}}$ . In this case, we need to search for an eligible group on the next link where the flow experiences the next maximum loss rate. This procedure repeats until all intermediate links are searched or the expected E2E loss rate becomes lower than the E2E

loss threshold:

$$P_{C_i, sd}^{e2e} \leq \overline{P_{C_i}^{e2e}}. \quad (4.23)$$



Step 1: Search for an eligible higher priority-group on a link.

Step 2: Repeat the searching procedure link by link from the link where the flow suffers from the highest loss rate to the link where the flow experiences the lowest loss rate.

Figure 4.3 Illustration of Priority-level Upgrading Mechanism

Along the path of the flow, there could be multiple links where its priority-levels are upgraded. Thus, the expected E2E loss rate of the flow after priority-level upgrading is calculated as:

$$P_{C_i, sd}^{e2e} = 1 - \prod_{k=1}^h (1 - p_{C_i, sd}^{i^k}), \quad (4.24)$$

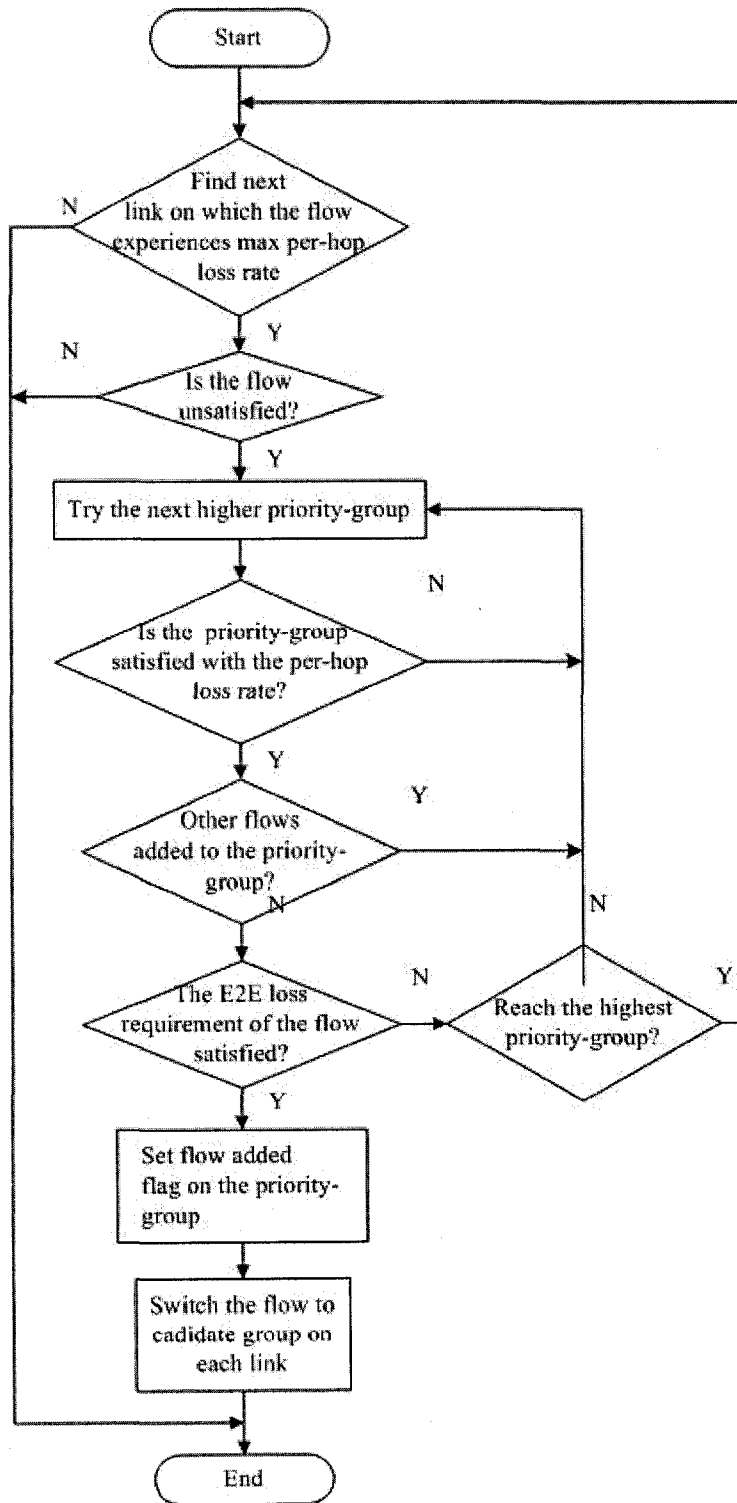


Figure 4.4 Flowchart of Priority-level Upgrading Mechanism

where  $p_{C_i,sd}^{*k}$  is the expected per-hop loss rate on the  $k$ th hop along the path. Therefore,

$$P_{C_i,sd}^{*e2e} = 1 - \prod_{\{l_{mn} \in r_{sd}\}} (1 - p_{C_i,sd}^{*mn}), \quad (4.25)$$

where  $p_{C_i,sd}^{*mn}$  is the expected per-hop loss rate of the flow  $f_{i,sd}$  on link  $l_{m,n}$ .

Further, the expected per-hop loss rate of the flow  $f_{i,sd}$  on a link  $l_{m,n}$  where no eligible group is found is equal to current group loss rate of the flow on the link ( $p_{G_j}^{*mn}$ ), and it is expected to be the per-hop loss threshold of the flow ( $\overline{p_{C_i,sd}}$ ) on each of the links where an eligible new group is available:

$$p_{C_i,sd}^{*mn} = \begin{cases} p_{G_j}^{*mn}, & \text{if } j' = j \\ \overline{p_{C_i,sd}}, & \text{if } 0 \leq j' < j \end{cases} \quad (4.26)$$

Therefore, the expected E2E loss rate of the flow can be calculated as:

$$P_{C_i,sd}^{*e2e} = 1 - \prod_{\{j'=j\}} (1 - p_{G_j}^{*mn}) \prod_{\{0 \leq j' < j\}} (1 - \overline{p_{C_i,sd}}). \quad (4.27)$$

Once the expected E2E loss rate of the flow is satisfied or all the links along the path has been searched, the higher priority-group searching procedure is finished. Then, the flow is switched to the eligible priority-group on each of the intermediate links where the eligible priority-groups are found. In other words, the table on each intermediate link is updated so that the bursts of the flow are given a new label that corresponds to the new priority-group. Therefore, the flow is assigned to the new higher priority-groups and the arriving bursts of

the flow will be attached a label corresponding to the new group in the next time-cycle.

Figure 4.4 shows the flowchart of the priority-level upgrading mechanism for an unsatisfied flow  $f_{C_i,sd}$ .

### 4.5.2 Priority-Level Degrading (PLD) Mechanism

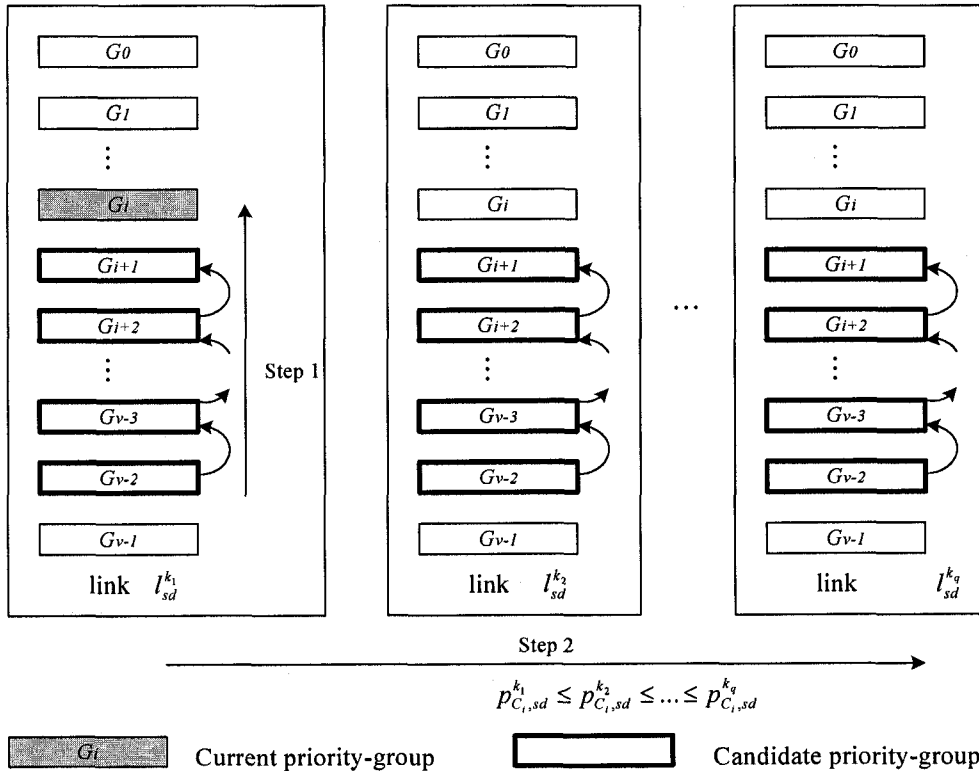
In the PLU mechanism, the priority-levels of the unsatisfied flows are upgraded in every time-cycle. Thus, the number of unsatisfied PG flows decreased gradually. However, the PLU mechanism makes the PG classes consume more and more bandwidth, and thus bursts of the BE class will get less and less bandwidth. As a result, the loss rate of the BE class traffic gets higher and higher. To reduce the expense of the BE class, we propose another mechanism, which is called priority-level degrading (PLD) mechanism.

In a network, a satisfied PG flow may experience an E2E loss rate that is much lower than its E2E loss threshold. In this case, we say it consumes more bandwidth than necessary. To save bandwidth for the BE class traffic, the E2E loss rates of the satisfied PG flows can be increased towards their E2E loss thresholds by degrading their priority-levels on their intermediate links. In this way, the bandwidth consumed by the satisfied PG flows can be reduced. As a result, the BE traffic can get more bandwidth and its loss rate can be reduced.

Similar to the procedure of PLU, in order to degrade the priority-levels of a satisfied PG flow, we need to find eligible priority-groups on the intermediate links before switching the flow to the new groups on the links. Here, we search the intermediate links for lower

priority-groups instead of higher priority-groups. If the E2E loss rate of a satisfied flow is too close to its E2E loss threshold, we will not degrade its priority-levels. Otherwise, it will be more likely to become an unsatisfied flow. To avoid this scenario, we can set a *degrade safety constant*  $\Delta$ , which controls when a satisfied flow can be degraded. A flow  $f_{C_i,sd}$  cannot be degraded unless it satisfies:

$$P_{C_i,sd}^{e2e} \leq \Delta \overline{P_{C_i}^{e2e}} \quad (0 < \Delta < 1) \quad (4.28)$$



- Step 1: Search for an eligible lower priority-group on a link.
- Step 2: Repeat the searching procedure link by link from the link where the flow experiences from the lowest loss rate to the link where the flow suffers from the highest loss rate.

Figure 4.5 Illustration of Priority-Level Degrading Mechanism

Figure 4.5 illustrates the eligible lower priority-group searching procedure. This

procedure starts from a link where the satisfied flow experiences the lowest per-hop loss rate, which is lower than its per-hop loss threshold. In addition, the candidate priority-levels on a link must be lower than the current priority-level of the flow. Suppose the flow belongs to group  $G_j$  and the system supports  $v$  priority-levels on a link, the candidate groups should be from  $G_{j+1}$  to  $G_{v-2}$  (Group  $G_{v-1}$  dedicates to flows of the BE class). On a specific link, searching for the eligible lower priority-level starts from the lowest priority-group  $G_{v-2}$  and ends at group  $G_{j+1}$ .

Moreover, the searching procedure goes through the links in an ascending order of the per-hop loss rates experienced by the satisfied flow. On each link, the searching procedure ends once the expected E2E loss rate of the flow is lower than its E2E loss threshold or all the candidate groups have been searched. Here, the expected E2E loss rate can be estimated using (4.25). Figure 4.6 shows the flowchart of priority-level degrading for a satisfied flow  $f_{C_i,sd}$ .

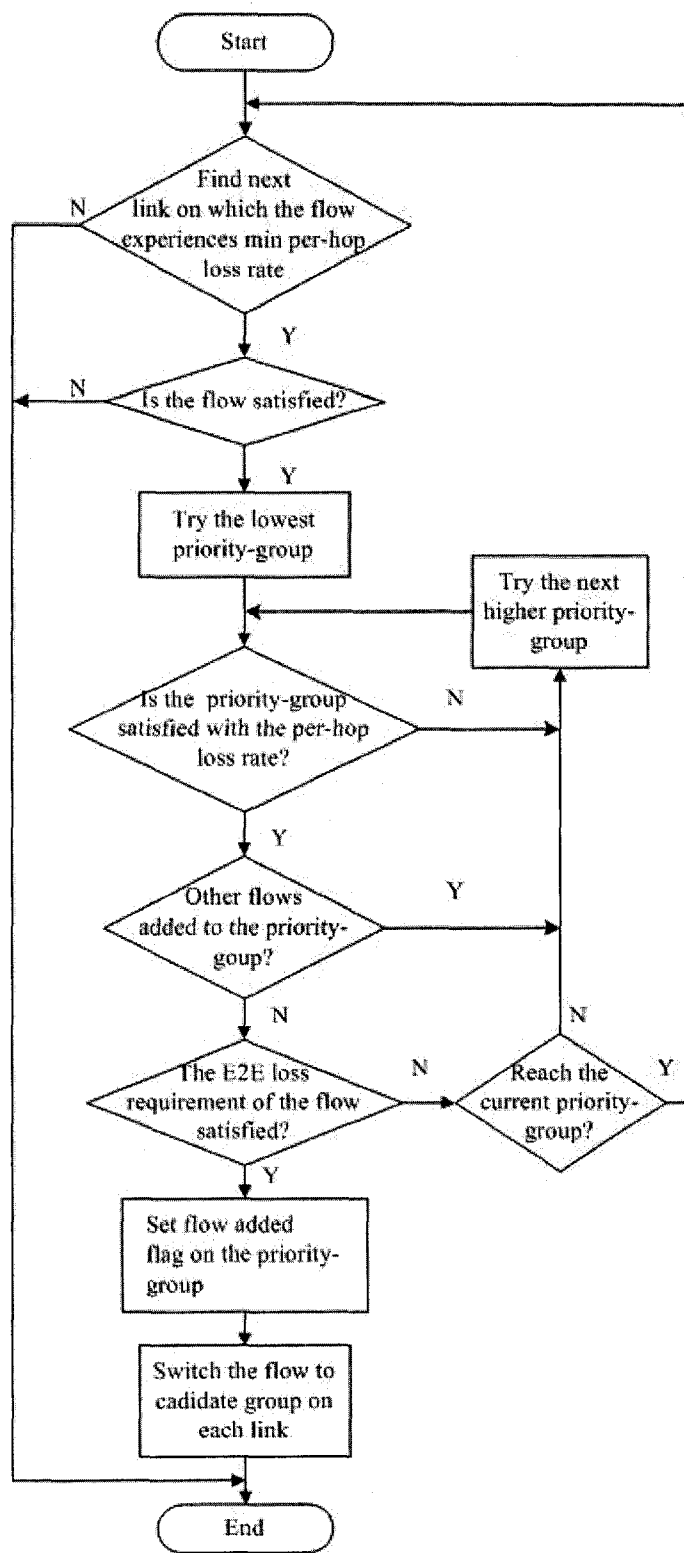


Figure 4.6 Flowchart of Priority-Level Degrading Mechanism

### 4.5.3 Integrated Self-adaptive Algorithm

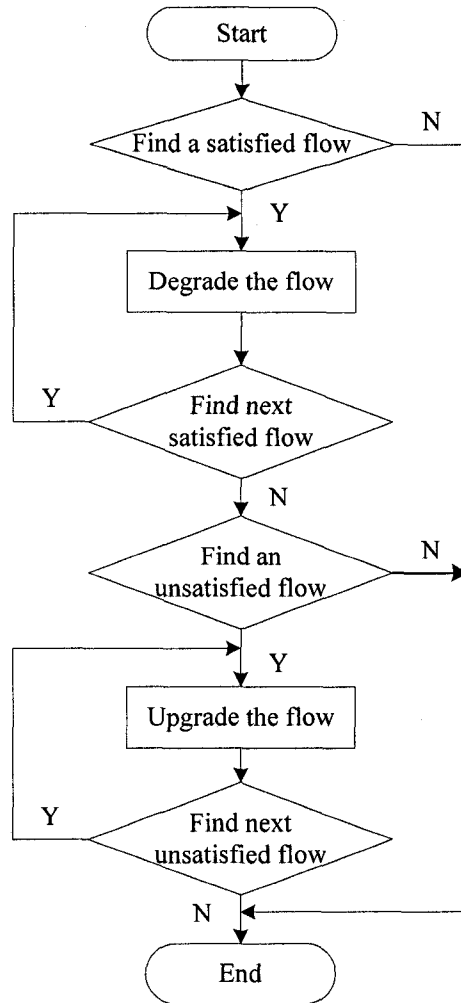


Figure 4.7 Flowchart of Self-adaptive Algorithm

As we discussed in the above sections, the PLU mechanism can reduce the number of unsatisfied flows in a network with the expense of the loss rate of the BE class. On the contrary, the PLD mechanism can lower down the loss rate of the BE class traffic. To combine the advantages of the PLU and PLD mechanisms, we can integrate the two mechanisms into a self-adaptive algorithm, which is run at every core node periodically. In

this algorithm, the PLD mechanism is implemented first, and then the PLU mechanism is implemented. In this way, the satisfied PG flows degrade their priority-levels first and make room for the unsatisfied PG flows to upgrade their priority-levels. What we need to mention is that the self-adaptive algorithm induces extra computation costs. At each core node, the PLD and PLU mechanisms need to be run periodically. During every time cycle, the core node needs to search for an eligible lower priority-level for every satisfied PG flow, and at the same time, it needs to search for an eligible higher priority-level for every unsatisfied PG flow.

The flowchart of the integrated algorithm is shown in Figure 4.7.

## 4.6 Summary

This chapter is dedicated to the absolute QoS differentiation on an E2E basis. We apply the ERPS scheme over an entire network to provide an absolute E2E QoS differentiation.

In this chapter, we have first presented system architecture. To guarantee the E2E loss requirement of a flow, which is defined as the traffic of a specific class between a specific source-destination pair, we need first to set a per-hop loss threshold on each intermediate link along its path. In order to set the per-hop loss threshold on each intermediate link, and at the same time, to achieve a balance of scalability and unnecessary bandwidth consumption, we have proposed two optimized priority-grouping techniques: the *optimized priority-grouping with single-class constraint (OPG-SC)* and the *optimized priority-grouping without single-class constraint (OPG-NC)*.

In the OPG-SC technique, each priority-group is composed of flows of the same service class. In addition, the priority-groups belonging to the same service class are next to each other in the sequence of the priority-groups. Thus, the priority-groups of a higher class can be sure to have a higher priority than those of a lower class. However, it makes PG classes consume more bandwidth unnecessarily. On the contrary, in the OPG-NC technique, each priority-group can be composed of flows belonging to different classes. This technique minimizes the unnecessary bandwidth consumption and makes the BE class traffic experience lower loss rate.

To cope with traffic-fluctuation and load-unbalance in networks, we have proposed the priority-level upgrading (PLU) mechanism and the priority-level degrading (PLD) mechanism. The PLU mechanism can reduce the number of unsatisfied flows (the flows that suffer from E2E loss rates higher than their respective E2E loss thresholds) in the network by upgrading the priority-levels of every unsatisfied flow on its intermediate links. However, upgrading the priority-levels makes the PG class flows consume more bandwidth. As a result, the loss rate of the BE class is increased. On the contrary, by degrading the priority-levels of the satisfied flows whose E2E loss rates are much lower than their E2E loss threshold, the PLD mechanism tries to increase the E2E loss rates of the satisfied flows while keeping them lower than their E2E loss thresholds. Therefore, it makes room to accommodate bursts of the unsatisfied flows or the BE class traffic. Finally, we have presented an integrated self-adaptive algorithm, which integrated the PLU mechanism and the PLD mechanism. The integrated algorithm can reduce the number of unsatisfied flows with the minimum expense on the loss rate of the BE class traffic.

In the next chapter, we will present the numerical examples and results to compare the performance of the proposed priority-level grouping techniques to that of the existing priority-level grouping technique. Also, the performance of the self-adaptive algorithm will be compared to that of the pure PLU and PLD mechanisms.

# Chapter 5

## Simulation Results and Analysis

### 5.1 Introduction

In Chapter 3, we have proposed the RPS scheme to provide a per-hop absolute QoS differentiation. An analytical model has also been presented. Then, a variety of RPS-based schemes were presented: RPS-SWG, RPS-DWG, RPS-ESWG, RPS-EDWG and ERPS. In this chapter, we validate the proposed RPS models and demonstrate its bandwidth utilization efficiency compared to the existing EDS and EDS-DWG schemes. We also compare the proposed BED and BEP mechanisms in the RPS scheme. The proposed SPT and SPG mechanisms are compared as well. In addition, we compare the performance of the RPS-based schemes via simulations.

In Chapter 4, we have presented two optimized priority-grouping (OPG) techniques,

OPG-SC and OPG-NC, for setting the per-hop loss thresholds along the path of each flow. Also, to cope with the problems of traffic-fluctuation and load-unbalance, we have also proposed the integrated self-adaptive algorithm, which integrates the PLU and PLD mechanisms. In this chapter, we describe the simulation models, followed by simulation results and performance analysis. We first compare the performance of OPG-SC and OPG-NC. Then, the integrated self-adaptive algorithm is compared to PLU and PLD in an OPG-SC-based network and an OPG-NC-based network respectively. Finally, the performance of the self-adaptive algorithm in the OPG-SC-based network is compared to that in the OPG-NC-based network. The simulation programs are written in JAVA language.

## **5.2 Per-hop QoS Differentiation Schemes**

### **5.2.1 Simulation Setup**

The simulations are conducted on a link between two core nodes in an OBS network. The basic simulation assumptions are as follows:

- There are 16 wavelengths on the link.
- The transmission rate on a wavelength is 10Gb/s.
- Bursts arrive at the link following a Poisson distribution with rate  $\lambda$ .
- Burst size is exponentially distributed with an average size of  $10^6$  bits.
- The core node has full wavelength conversion capability.

- There is no buffering at the core nodes.

In this section, we conduct simulations in a 3-class network with 2 PG classes ( $C_0$  and  $C_1$ ) and a BE class ( $C_2$ ), and a 2-class network with a PG class ( $C_0$ ) and a BE class ( $C_1$ ). In the 3-class network, the bursts of class  $C_0$ ,  $C_1$  and  $C_2$  comprise 10%, 30% and 60% of the traffic respectively. In addition, we assume that the loss thresholds of class  $C_0$  and  $C_1$  are 0.002 and 0.005 respectively. In the 2-class network, 30% of the traffic is from class  $C_0$  and 70% of the traffic is from class  $C_1$ , and the loss threshold of class  $C_0$  is 0.001.

## 5.2.2 RPS Model

In this section, we validate the proposed RPS model and demonstrate its bandwidth utilization efficiency compared to EDS and EDS-DWG. In addition, the proposed RPS-based schemes are compared to each other via simulations.

### 5.2.2.1 Performance Comparison of RPS, EDS and EDS-DWG

We first compare the performance of the proposed RPS to the existing EDS and EDS-DWG schemes in a 2-class system.

Figure 5.1(a) and Figure 5.1(b) show the burst loss rates of class  $C_0$  and  $C_1$  versus load respectively. We can observe from Figure 5.1(a) that all the schemes can make the loss rate of class  $C_0$  close to its loss threshold (0.001). The loss rate of class  $C_0$  is closer to the loss threshold with the RPS scheme, while the EDS scheme makes the lowest loss rate. However, the loss rate of class  $C_0$  in the RPS scheme exceeds the threshold occasionally.

In Figure 5.1(b), we can observe distinct differences of  $C_1$  loss rate with the different schemes. When the load is higher than 0.4, class  $C_1$  experiences the lowest loss rate with RPS. Also, the difference gets bigger when the load gets heavier. This is because of the fact that the early-drop mechanism is triggered in the EDS and the EDS-DWG schemes when the load is higher than 0.4 and  $C_1$  bursts are dropped intentionally in order to reduce the chance of contention with  $C_0$  bursts. On the other hand, in the RPS scheme, with its reserve-and-preempt mechanism, the  $C_1$  bursts are not dropped before contentions occur. Instead, they can reserve as much bandwidth as they can as long as the loss rate of class  $C_0$  is not exceeding its loss threshold.

Figure 5.1(c) shows a plot for the bandwidth utilization versus load. We can observe that RPS utilizes the bandwidth most efficiently. Before the load reaches 0.4, all the 3 schemes have the same linear increasing bandwidth utilization. However, when the load is higher than 0.4, RPS performs much better than the other two schemes and its bandwidth utilization keeps increasing. When the load is 1.0, the bandwidth utilization of RPS is 0.83, while the bandwidth utilizations of EDS and EDS-DWG are only 0.4 and 0.48 respectively. After the load exceeds 0.4, EDS keeps the bandwidth utilization at 0.4, because the early-drop mechanism is triggered and  $C_0$  bursts keep being dropped. In addition, the bandwidth utilization of EDS-DWG increases until the load is increased to 0.7, where it reaches the maximum value 0.5. After that, the bandwidth utilization of EDS-DWG decreases slowly to 0.48 when the load reaches 0.9. The reason for the variation is that when the load is between 0.4 and 0.7, the EDS-DWG scheme allows treating some  $C_1$  bursts as class  $C_0$  bursts and lets them to share the bandwidth in the wavelength group of class  $C_0$ . After the load reaches 0.7,

fewer and fewer  $C_1$  bursts are treated as  $C_0$  bursts. Thus, EDS-DWG bandwidth utilization drops to 0.48 when the load is 1.0.

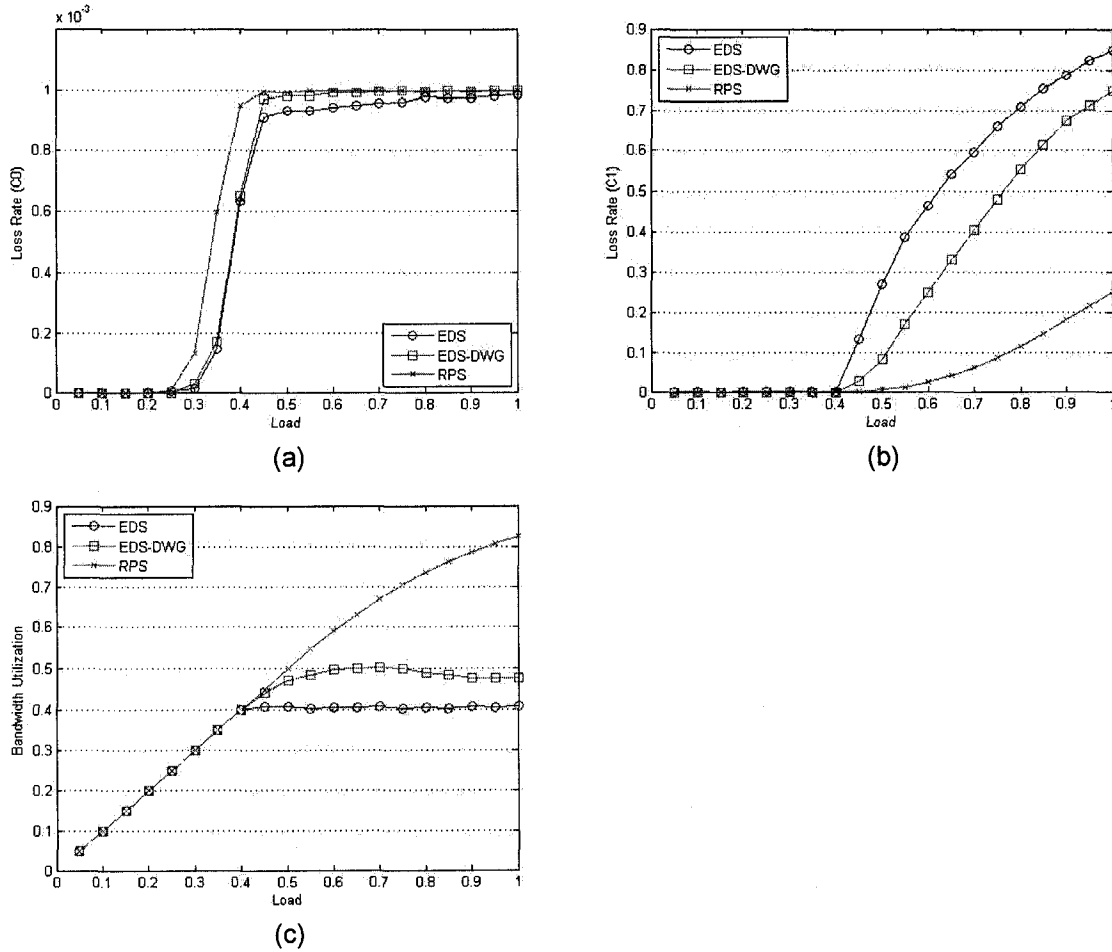


Figure 5.1 Performance Comparison of RPS, EDS and EDS-DWG

### 5.2.2.2 Performance Comparison of BED and BEP

Figure 5.2 and Figure 5.3 show the performance comparison of the BED and BEP mechanisms in a 2-class system and a 3-class system respectively. In Figure 5.2(a), when the load is lower than 0.45, the  $C_0$  loss rate with BEP is higher than that with the BED approach.

As a result, the  $C_1$  loss rate with BEP is lower than that with BED when the load is lower than 0.45, as shown in Figure 5.2(b). After the load exceeds 0.45, both of BED and BEP keep the  $C_0$  loss rate close to its threshold (Figure 5.2(a)), and the  $C_1$  traffic experiences the same loss rate with both BED and BEP approaches (Figure 5.2(b)).

Similarly, in Figure 5.3 (a), when the load is lower than 0.5, BEP makes the loss rates of both of the PG classes ( $C_0$  and  $C_1$ ) higher than BED does. After the load exceeds 0.5, both BED and BEP keep the loss rates of the PG classes close to their loss thresholds (0.002 and 0.005). Correspondingly, in Figure 5.3(b), the BE class ( $C_2$ ) experiences lower loss rate in the BEP approach than in the BED approach when the load is not heavy.

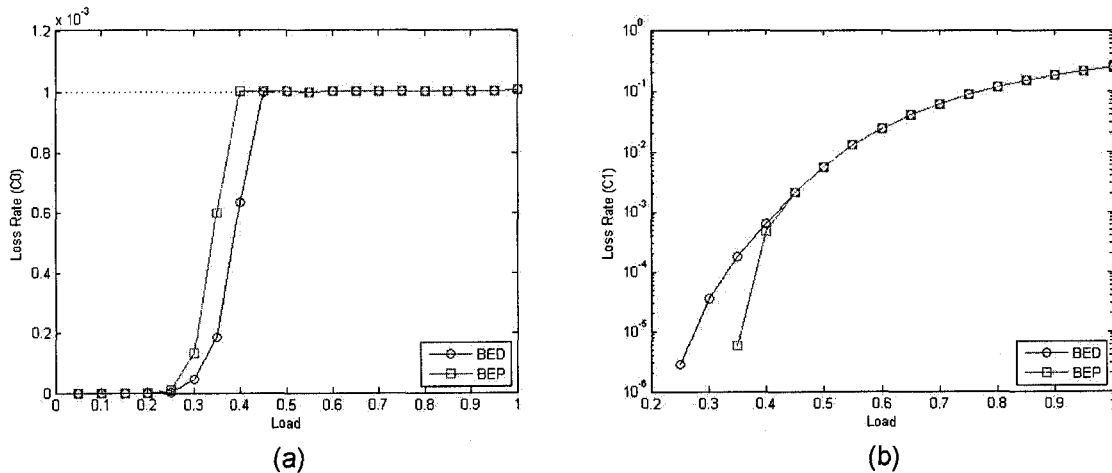


Figure 5.2 Performance Comparison of BED and BEP in a 2-Class System

The reason for the performance difference of BED and BEP is that when the load is low, BEP allows the arriving BE bursts to preempt the scheduled PG class bursts that are not in danger of violating their thresholds. As a result, the BEP approach makes the loss rate of each PG class higher. Therefore, it also makes the loss rate of the BE class lower than the BED

approach does.

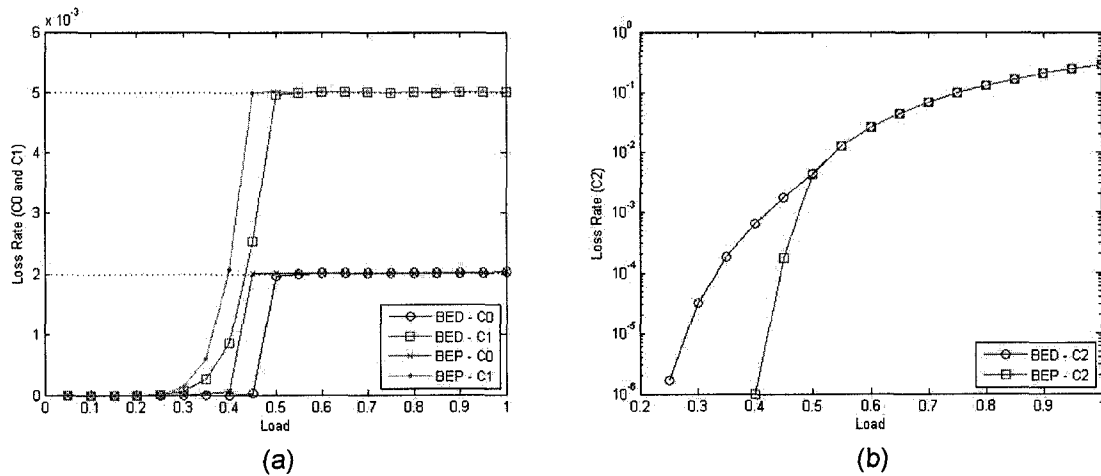


Figure 5.3 Performance Comparison of BED and BEP in a 3-Class System

### 5.2.2.3 Performance Comparison of SPT and SPG

To compare the performance of the SPT mechanism and the SPG mechanism, we conduct simulations in a 2-class system and a 3-class system, in both of which the loss rates of different classes are plotted versus load and time.

Figure 5.4 and Figure 5.5 show the loss rates of the 2 classes versus load and time respectively. In Figure 5.4(a), we observe that in the SPT mechanism, the loss rate of class  $C_0$  exceeds its threshold from time to time, while in the SPG mechanism with guard-space  $\delta=0.0002$  and  $\delta=0.0005$ , its loss rate is kept under its threshold. Moreover, the greater the guard-space, the lower the loss rate. This is because with a greater guard-space, bursts of the PG class ( $C_0$ ) are kept from being over-preempted by bursts of the BE class before the loss threshold of class  $C_0$  is breached. In Figure 5.4(b), we can observe that the two mechanisms provide similar loss rates to the BE class ( $C_1$ ).

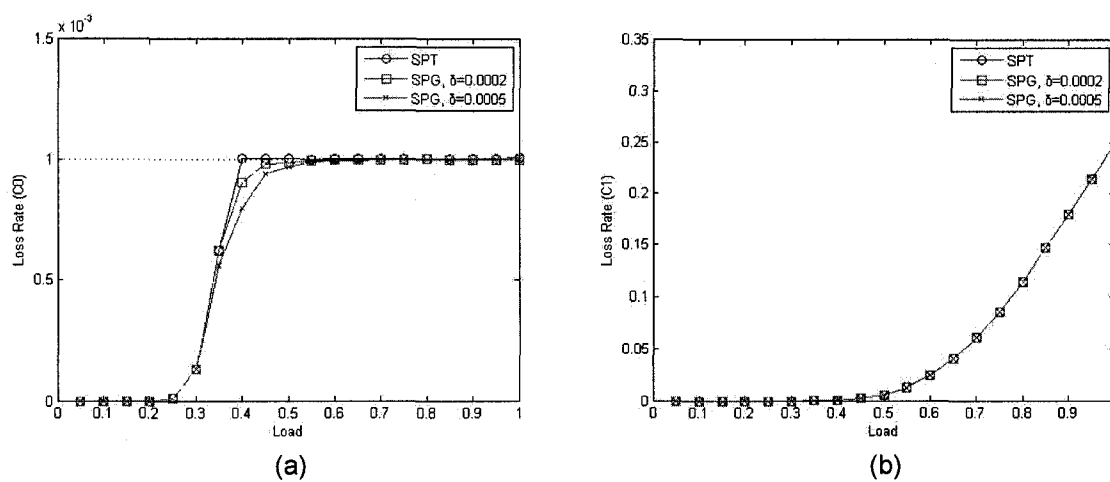


Figure 5.4 Performance Comparison of SPT and SPG in a 2-class System: Loss Rate vs. Load

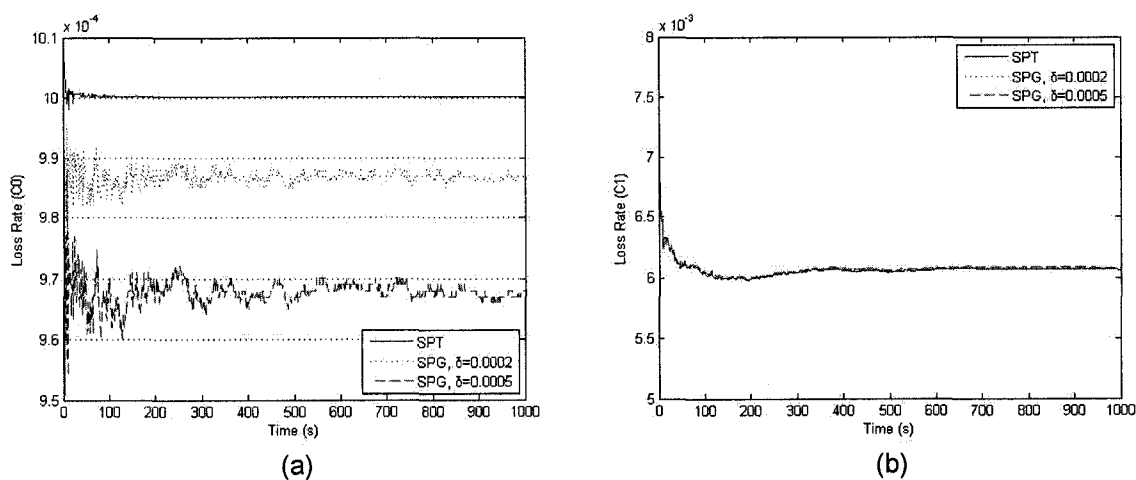


Figure 5.5 Performance Comparison of SPT and SPG in a 2-class System: Loss Rate vs. Time

From Figure 5.5 (a), we can observe that in time scale, the loss rate of class  $C_0$  in the SPT mechanism breaches its threshold (0.0001) occasionally. However, with guard-space  $\delta=0.0002$  and  $\delta=0.0005$ , its loss rate is around 0.0000987 and 0.0000968 respectively. The loss rate of the BE class ( $C_1$ ) in the SPG mechanism is similar to that in the SPT mechanism.

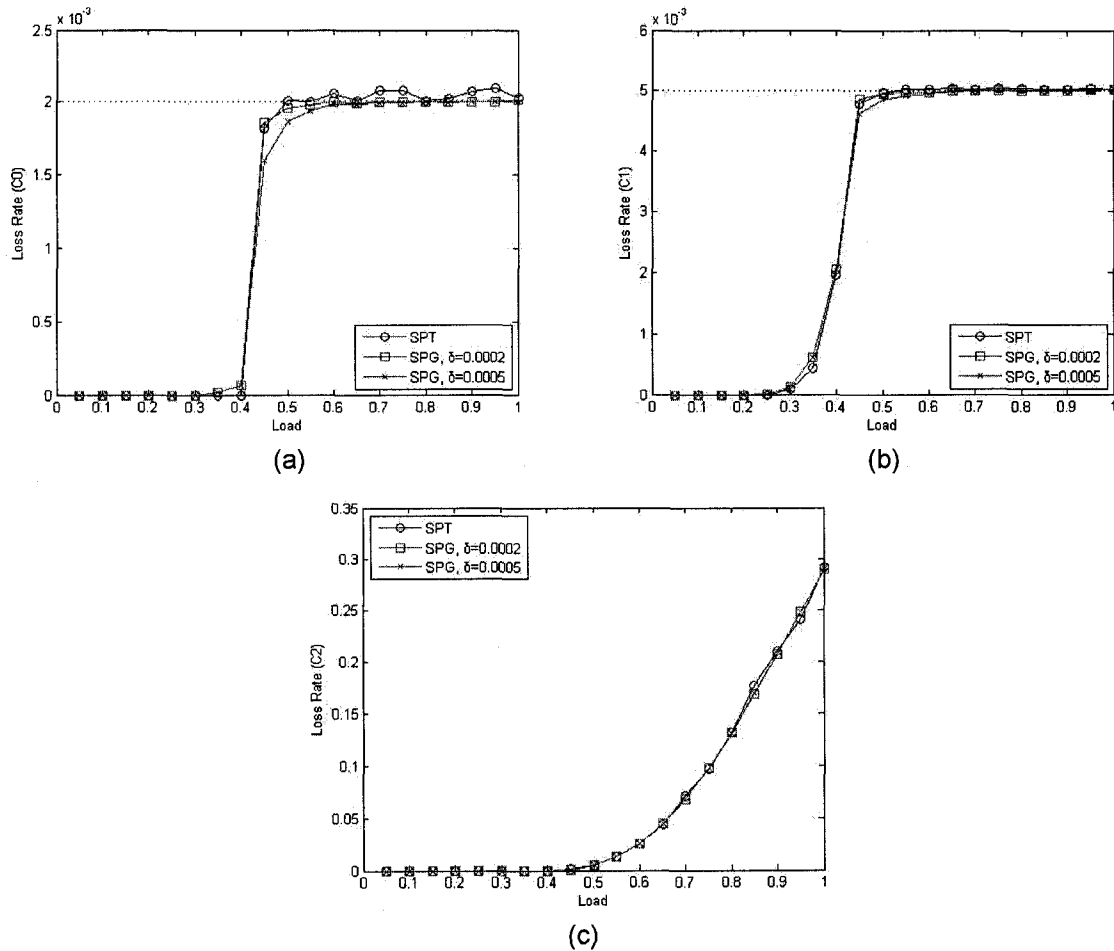


Figure 5.6 Performance Comparison of SPT and SPG in a 3-class System: Loss Rate vs. Load

Figure 5.6 (a), (b) and (c) show the loss rates of the two PG classes ( $C_0$  and  $C_1$ ) and the BE class ( $C_2$ ) versus load respectively. From Figure 5.6 (a) and (b), we observe that with the SPT mechanism, the loss rates of both  $C_0$  and  $C_1$  violate their respective loss threshold (0.0002 and 0.0005) occasionally. However, with the SPG, they are all kept under their loss thresholds. Figure 5.6(c) shows that the loss rate of the BE class ( $C_2$ ) with the SPG mechanism is similar to that with the SPT mechanism.

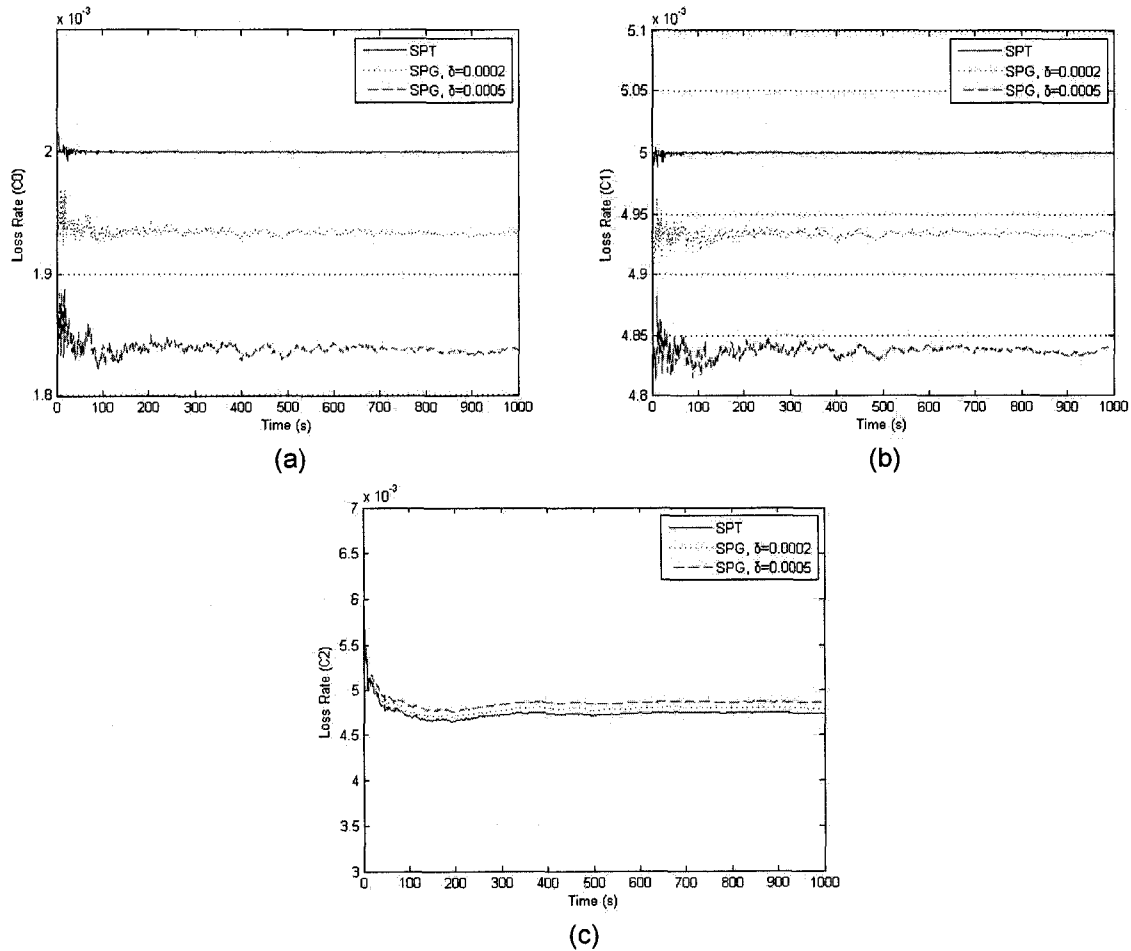


Figure 5.7 Performance Comparison of SPT and SPG in a 3-class System: Loss Rate vs. Time

Figure 5.7 shows the loss rates of the 3 classes versus time. In Figure 5.7 (a) and (b), similar to Figure 5.5, with SPG, the loss rates of the PG classes are guaranteed, and the greater the guard-space, the lower the loss rates of the PG classes. In Figure 5.7(c), we observe that the loss rates are similar, but the loss rate of  $C_2$  in the SPT mechanism is a little lower than those in the SPG mechanism with  $\delta=0.0002$  and  $\delta=0.0005$ . The SPG with  $\delta=0.0005$  suffers from the highest  $C_2$  loss rate. This is the tradeoff of lowering down the loss rates of the PG classes.

### 5.2.2.4 Validation of Analytical Model

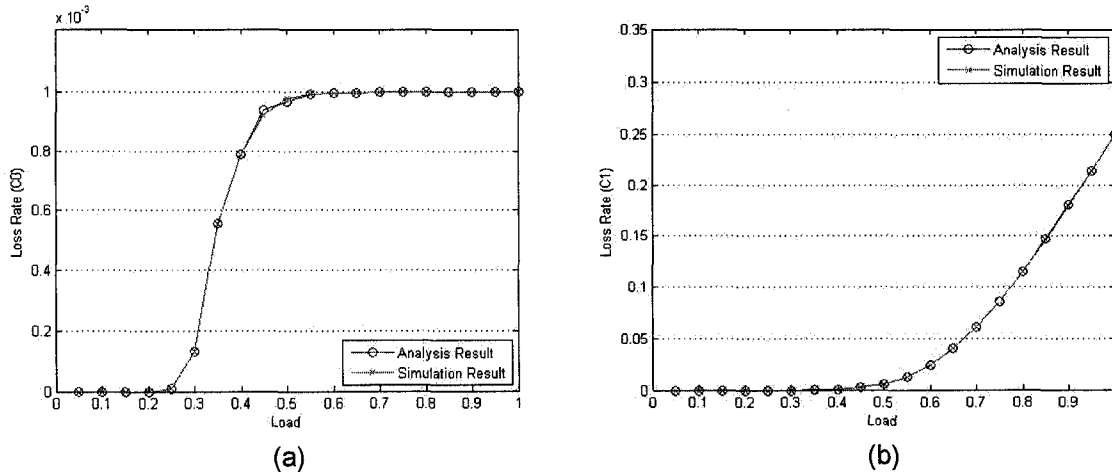


Figure 5.8 Analysis Model of RPS

Figure 5.8(a) and (b) compare the analytical results with the simulation results for the RPS scheme in a 2-class system. The analytical model is based on the mechanisms of SPG and BEP, and we set  $\delta=0.0005$ . We can see that the simulation results match closely with the analytical results. This proves the correctness of the analytical model.

## 5.2.3 Performance of RPS-based Schemes

### 5.2.3.1 RPS-SWG and RPS-DWG

Figure 5.9 shows the loss rates of the 2 PG classes versus load in a 3-class system. We can observe that when the load exceeds 1.25, the loss rates of both of the PG classes cannot be guaranteed. To make sure that the highest priority class can experience a guaranteed loss rate, we have integrated the RPS scheme and the wavelength grouping schemes, and proposed the

RPS-SWG scheme and the RPS-DWG scheme in Chapter 3.

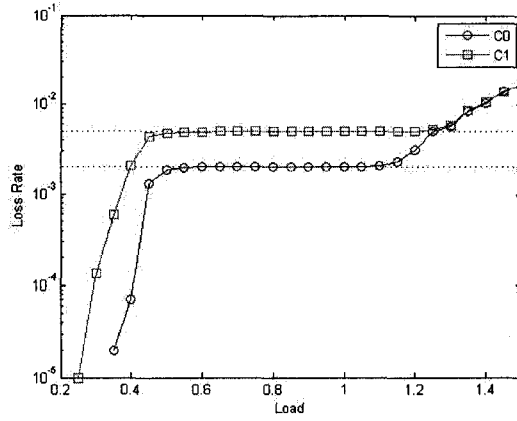


Figure 5.9 Performance of PG Classes in RPS scheme

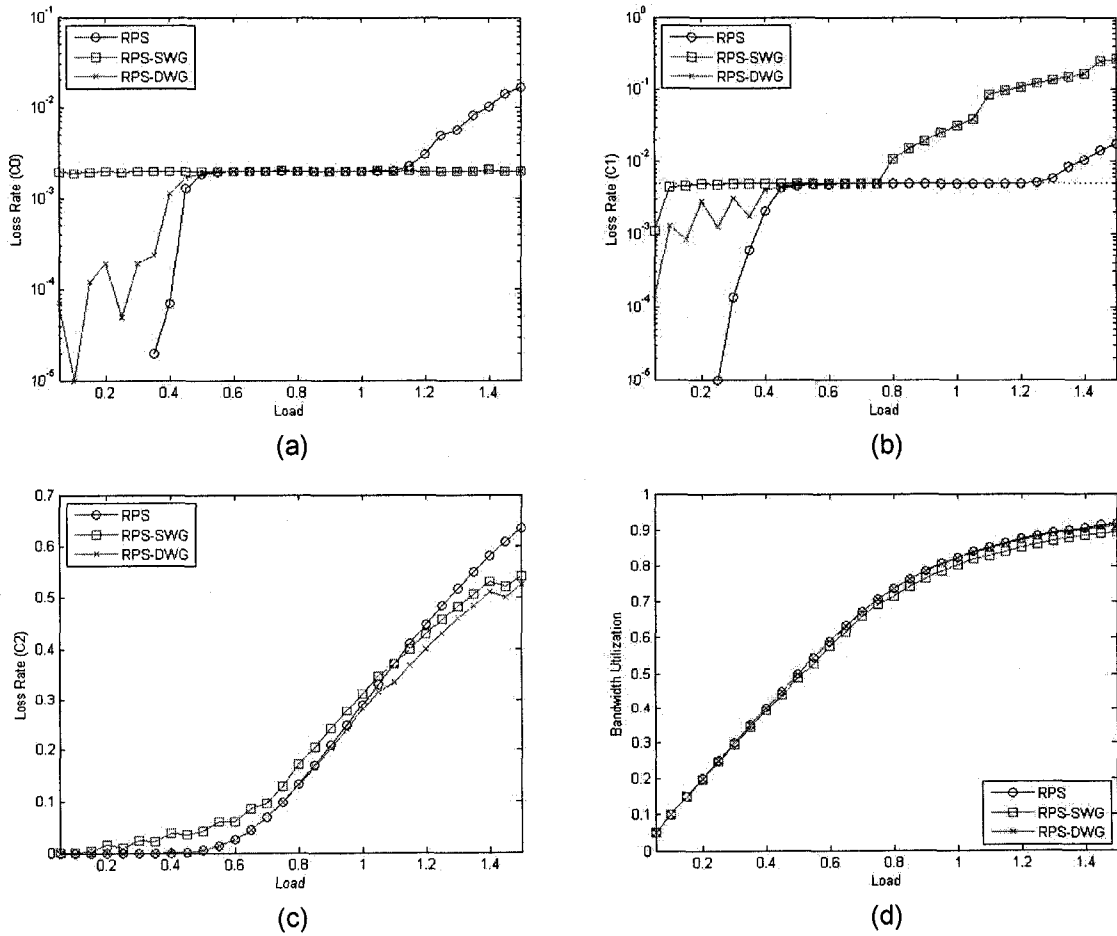


Figure 5.10 Performance Comparison of RPS, RPS-SWG and RPS-DWG

Figure 5.10 compares the performance of RPS-SWG and RPS-DWG to that of the pure RPS scheme. We can see that with RPS-SWG or RPS-DWG, the loss rate of  $C_0$  is guaranteed even when the load is heavy (as shown in Figure 5.10(a)). However, the integrated schemes sacrifice the performance of  $C_1$ . While the RPS scheme keeps the loss rate of  $C_1$  below its threshold until the load reaches 1.25, RPS-SWG or RPS-DWG cannot guarantee the loss rate of  $C_1$  once the load exceeds 0.75 (Figure 5.10(b)). From Figure 5.10(c), we can observe that the BE class ( $C_2$ ) experiences lower loss rate with RPS-DWG or RPS-SWG than that with the pure RPS scheme when the load is heavy. This is because with the wavelength grouping mechanisms, the spare bandwidth in the wavelength group of class  $C_0$  can only be shared by class  $C_2$  bursts. In addition, we can observe that with RPS-DWG, class  $C_2$  experiences the lowest loss rate. With the dynamic wavelength grouping mechanism, the scheduled BE bursts have fewer chances to be preempted by the arriving PG bursts because of the flexibility for the arriving PG bursts to choose wavelengths. Moreover, as shown in Figure 5.10(a), (b) and (c), when the load is not heavy, RPS-SWG makes every class experience the highest loss rate among the three schemes. This is because each arriving burst that belongs to a PG class can only be scheduled on the wavelengths dedicated to the PG class, thus each PG class ( $C_1$  or  $C_1$ ) suffers from higher loss rate (see Figure 5.10(a) and (b)). As a result, there is a higher chance for the PG class bursts to preempt the scheduled BE class bursts. Therefore, the loss rate of the BE class ( $C_2$ ) suffers from high loss rate as well (see Figure 5.10(c)). From Figure 5.10(d), we can observe that the RPS-SWG scheme utilizes bandwidth not as efficiently as the RPS scheme or the RPS-DWG scheme.

### 5.2.3.2 RPS-ESWG and RPS-EDWG

Because RPS-SWG and RPS-DWG cannot guarantee the loss rate of the lower-priority PG class  $C_l$  when the load is heavy, we have extended RPS-SWG and RPS-DWG and proposed the schemes of RPS-ESWG and RPS-EDWG in Chapter 3.

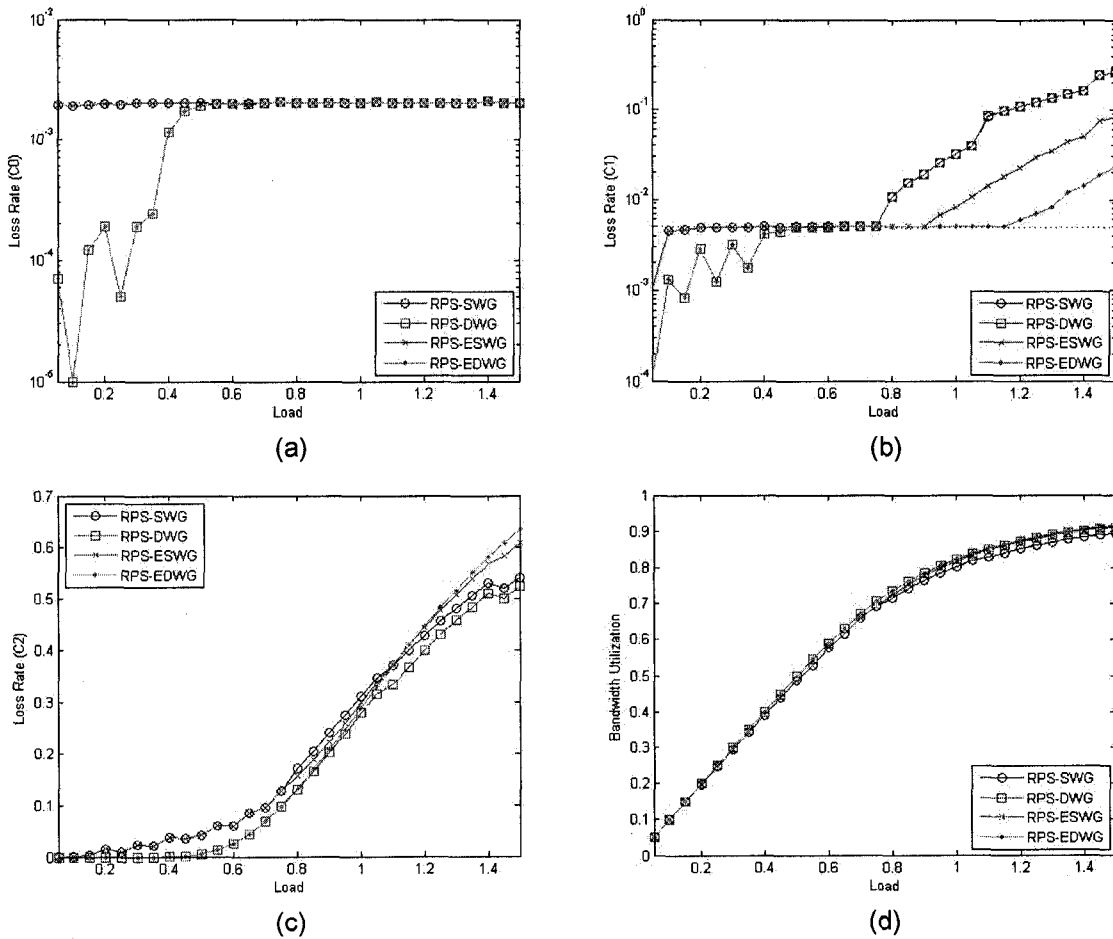


Figure 5.11 Performance Comparison of RPS-SWG, RPS-DWG, RPS-ESWG and RPS-EDWG

Figure 5.11(a) depicts the loss rate of class  $C_0$  with the two integrated schemes (RPS-SWG and RPS-DWG) and the two extended schemes (RPS-ESWG and RPS-EDWG). We can observe that the extended schemes can guarantee the loss rate of class  $C_0$  as well. In

Figure 5.11(b), the loss rate of class  $C_1$  is reduced with the extended schemes under heavy load. With RPS-SWG or RPS-DWG, the loss rate of class  $C_1$  cannot be guaranteed once the load exceeds 0.75. However, RPS-DSWG and RPS-EDWG can guarantee the loss rate of class  $C_1$  until the load reaches 0.9 and 1.15 respectively. Figure 5.11(c) compares the class  $C_2$  loss rate of the four schemes. When the load is light, RPS-DWG and RPS-EDWG perform better because the PG classes ( $C_0$  and  $C_1$ ) experience lower loss rates (see Figure 5.11(a) and (b)), and thus the PG bursts have a lower chance to preempt the scheduled BE ( $C_2$ ) bursts. However, when the load is heavy, class  $C_2$  suffers from higher loss rate with the extended schemes because more bandwidth is utilized by the class  $C_1$  bursts. From Figure 5.11 (d), we can see that RPS-DWG and RPD-EDWG utilize the bandwidth more efficiently.

In summary, the RPS-EDWG scheme outperforms the other 3 schemes in terms of loss rates and bandwidth utilization.

### 5.2.3.3 ERPS

Although the RPS-EDWG scheme outperforms the other schemes, it is complicated to implement because the system needs to allocate a certain number of wavelengths to each PG class and keep track the number of occupied wavelengths for each PG class. Therefore, the ERPS scheme has been proposed in Chapter 3.

Figure 5.12 depicts the performance of the ERPS scheme compared to that of the RPS-EDWG scheme. Both of the two schemes can guarantee the loss rate of  $C_0$  (Figure 5.12(a)), and the loss rate of  $C_1$  can be kept below its threshold when the load is not too

heavy (Figure 5.12(b)). In addition, the two schemes make the BE class ( $C_2$ ) experience almost the same loss rate as shown in Figure 5.12 (c). Also, they provide the same bandwidth utilization (Figure 5.12 (d)). The only difference between the two schemes is that the PG classes ( $C_0$  and  $C_1$ ) experience lower loss rates with ERPS when the load is light. The reason is that the ERPS scheme does not restrict the number of wavelengths that each PG class can occupy and the bursts of each PG class can occupy more wavelengths when the load is light. As a result, the ERPS scheme makes the loss rate of each PG class lower than the RPS-EDWG scheme does.

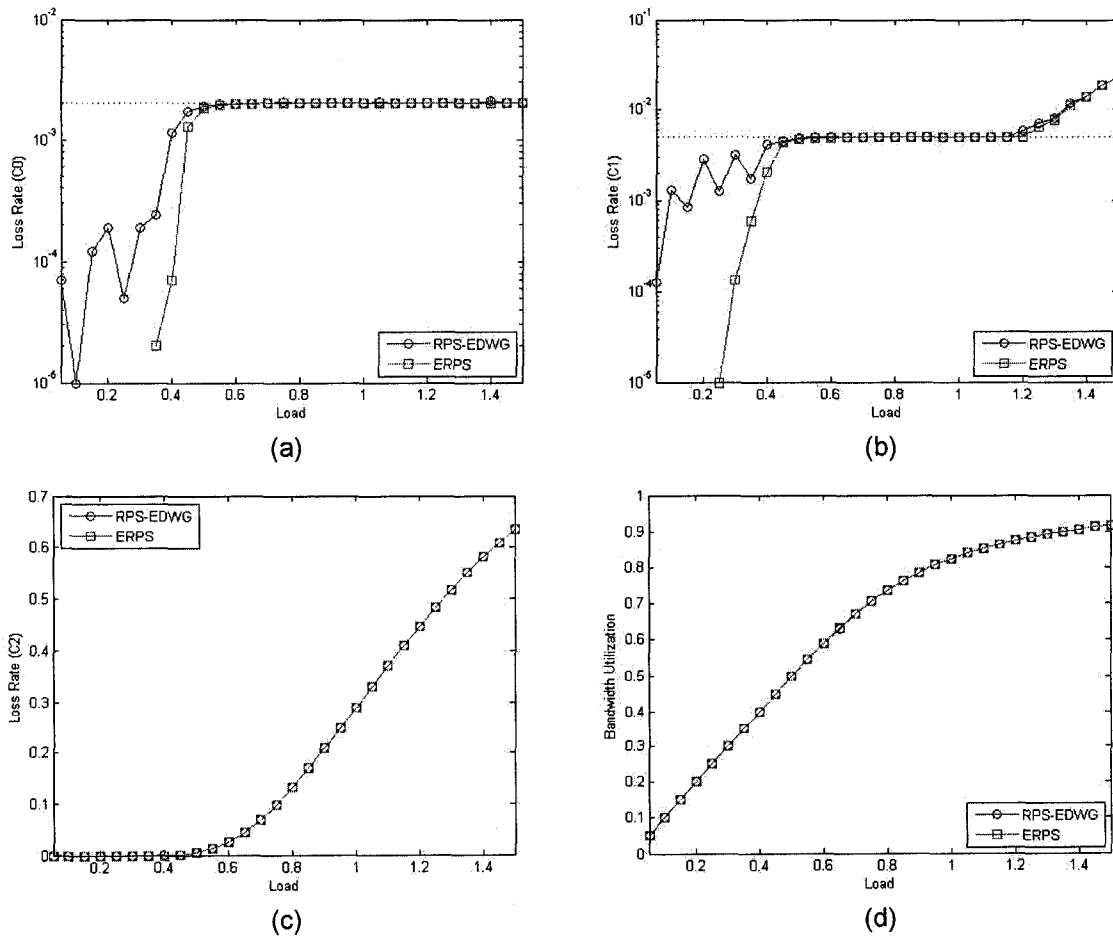


Figure 5.12 Performance Comparison of RPS-EDWG and ERPS

Figure 5.13 compares the performance of all of the proposed per-hop QoS differentiation schemes. In Figure 5.13(a), only the pure RPS scheme cannot guarantee the loss rate of  $C_0$  even when the load is heavy. In Figure 5.13(b), the loss rate of  $C_1$  can be guaranteed until the load reaches 0.75 with RPS-SWG or RPS-DWG. The loss rate of  $C_1$  can be improved with the extended schemes RPS-ESWG and RPS-EDWG. With RPS-ESWG, the loss rate of  $C_1$  is guaranteed until the load reaches 0.9. RPS-EDWG and ERPS can guarantee the loss rate of  $C_1$  before the load exceeds 1.2. In Figure 5.13(c), the loss rate of the BE class ( $C_2$ ) experiences lower loss rate with RPS-ESWG, RPS-EDWG or ERPS under light traffic load. However, when the traffic load becomes heavy, the loss rate of  $C_2$  is the highest with RPS-EDWG or ERPS. This is the tradeoff to lower down the loss rate of  $C_1$  while guaranteeing the loss rate of  $C_0$  under heavy traffic load. Figure 5.13(d) depicts the bandwidth utilization of all the proposed schemes. When the traffic load is heavier, the bandwidth utilization of RPS-SWG is a little lower than those of the other schemes, which are close to each other.

In conclusion, the ERPS scheme outperforms the other proposed schemes. We will apply the ERPS scheme to every core node of an OBS network to achieve E2E QoS differentiation in the following section.

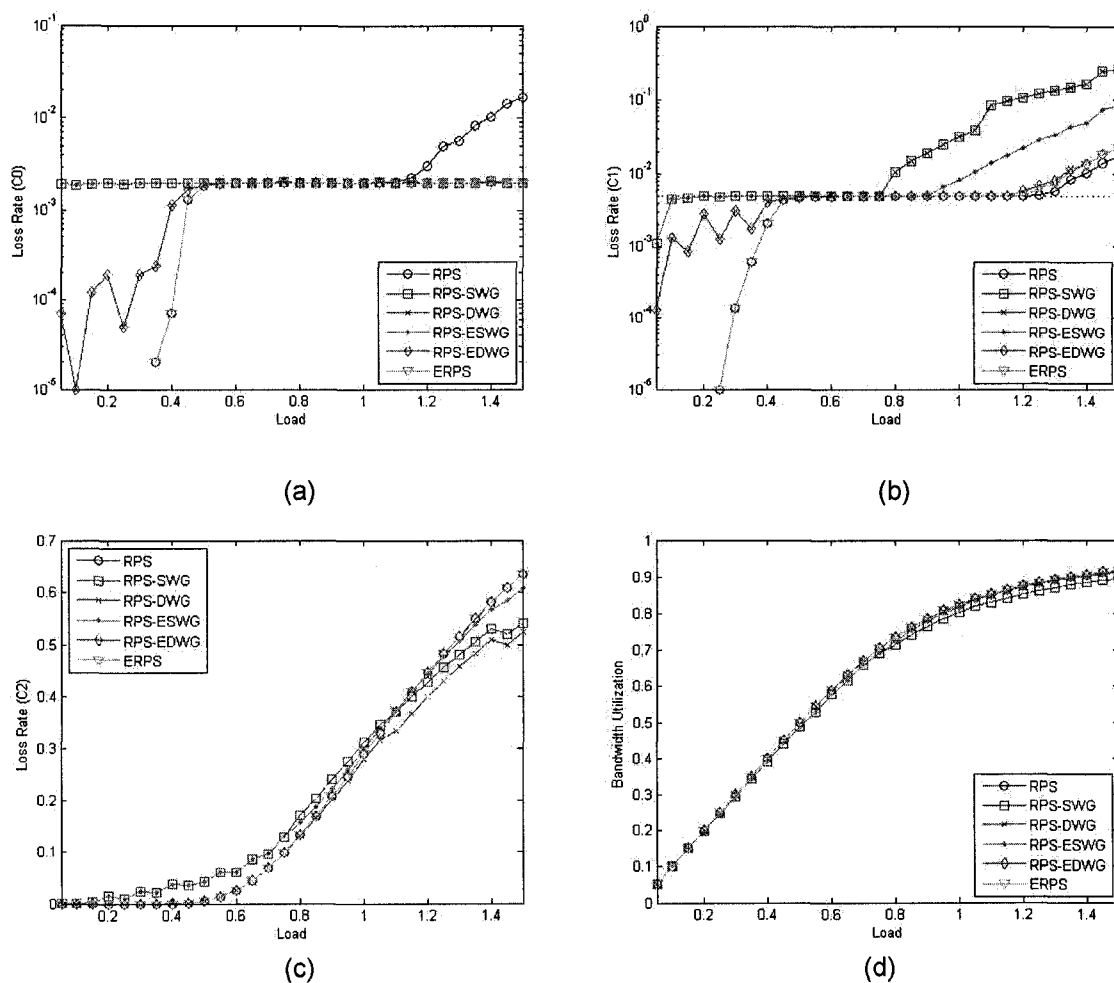


Figure 5.13 Performance Comparison of all of the proposed schemes

## 5.3 End-to-End QoS Differentiation

### 5.3.1 Simulation Setup

To apply ERPS to the core nodes in an OBS network, we conduct simulations over the entire network. The simulations are conducted for the NSF 14-node OBS network as shown in Figure 5.14.

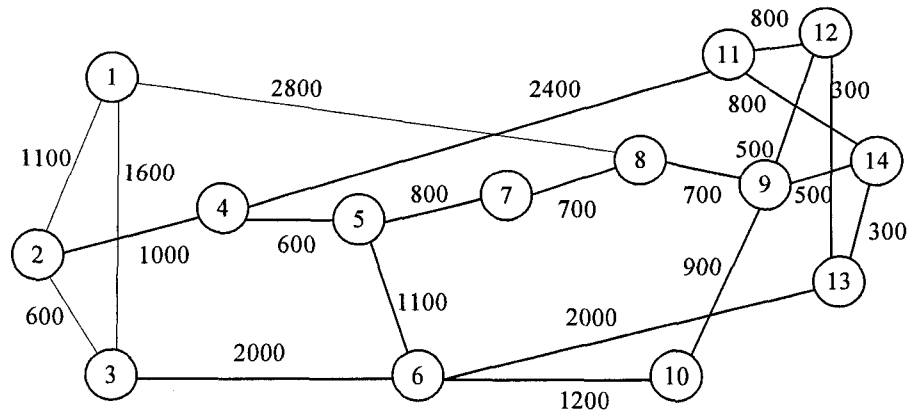


Figure 5.14 NSF 14-node Network

The basic simulation assumptions are as follows:

- There are 8 wavelengths on every link.
- The transmission rate on a wavelength is 10Gb/s.
- Bursts arrive at the edge nodes following a Poisson distribution with rate  $\lambda$ .
- The traffic is uniformly distributed among all of the source-destination pairs.
- Fixed shortest-path routing is used.
- Burst size is exponentially distributed with average size of  $10^6$  bits.
- The core nodes have full wavelength conversion capability.
- There is no buffering at the core node.
- There are 3 service classes in the network, where  $C_0$  and  $C_1$  are the PG classes and  $C_2$  is the BE class.
- Bursts of classes  $C_0$ ,  $C_1$  and  $C_2$  comprise 20%, 30% and 50% of the traffic respectively.

- The E2E loss thresholds of class  $C_0$  and  $C_1$  are 0.05 and 0.1 respectively.
- The system supports 5 priority-levels on each node, including a BE level.

### 5.3.2 Performance of Priority Grouping Techniques

To evaluate the performance of the proposed OPG-SC and OPG-NC schemes, we compare their performance to that of the existing fixed priority-grouping (FPG) scheme, both over the entire network and on bottleneck link  $l_{1,3}$ . The simulations on the FPG scheme are conducted in two priority-group combinations. In the first combination  $\{5, (1, 2, 3, 4)\}$ , flows with hop-distance 5 are assigned to a higher-priority group and those with hop-distances 1-4 are assigned to a lower-priority group. In the second combination  $\{(3, 4, 5), (1, 2)\}$ , flows with hop-distances 3, 4, and 5 are assigned to a higher-priority group and flows with hop-distances 1 and 2 are assigned to a lower-priority group.

Figure 5.15 compares OPG-SC and OPG-NC with the existing FPG scheme over the entire OBS network. We can observe from Figure 5.15 (a) and (b) that the proposed OPG schemes provide higher loss rates for class  $C_0$  and class  $C_1$  than FPG does while all of the schemes can keep the overall loss rate of each PG class below its E2E threshold. With OPG-NC, the PG classes experience the highest E2E loss rates. Figure 5.15 (c) shows that the BE class experiences the lowest loss rates with OPG-NC and suffers from high loss rates with the existing FPG scheme. The reason is that OPG-NC reduces the bandwidth consumed by the PG classes and the saved bandwidth is utilized by the BE class.

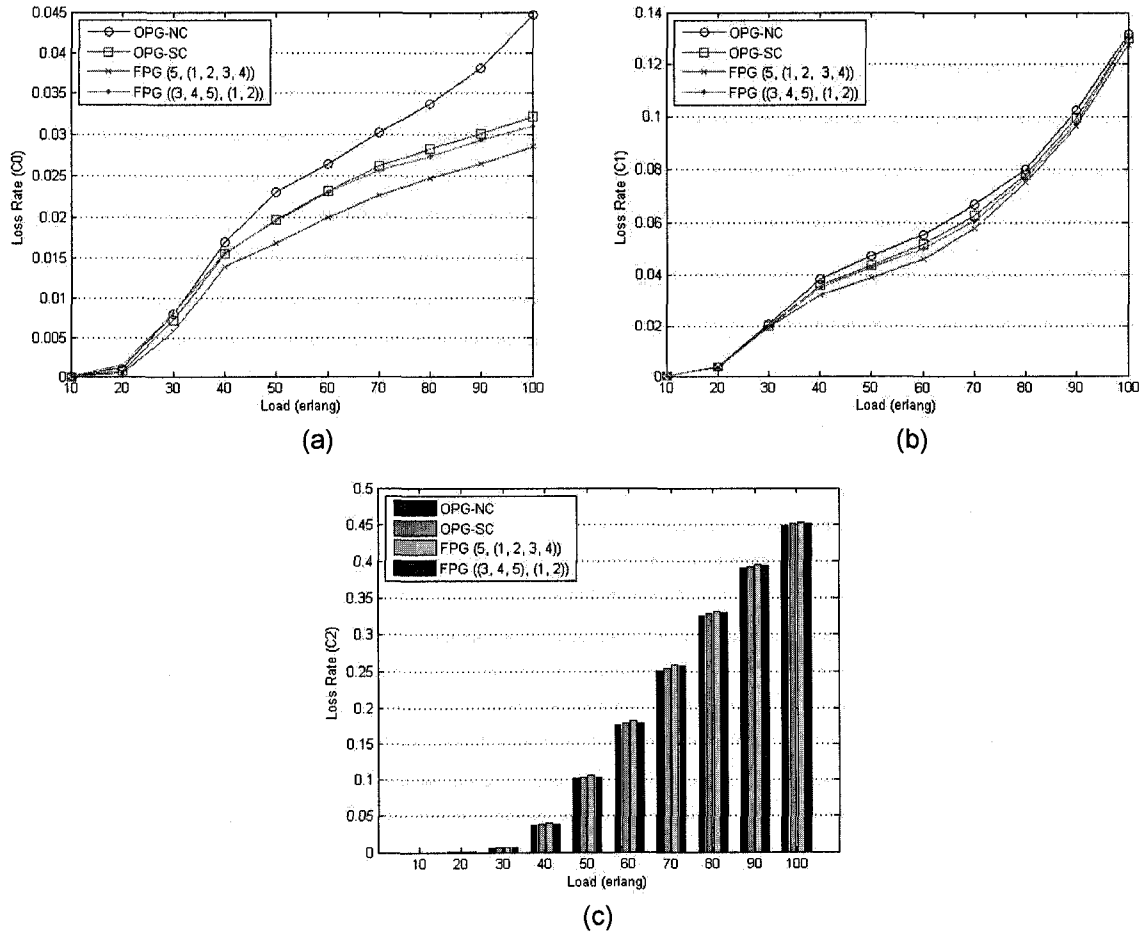


Figure 5.15 Overall Performance Comparison of OPG-SC and OPG-NC

Since the traffic is uniformly distributed among all source-destination pairs, we also study the performance of OPG-SC and OPG-NC on the bottleneck link  $l_{1,3}$ . Figure 5.16 depicts the comparison of the proposed OPG schemes and the existing FPG scheme on link  $l_{1,3}$ . In Figure 5.16(a), class  $C_0$  experiences the highest loss rate with OPG-NC, and the FPG scheme with combination  $\{5, (1, 2, 3, 4)\}$  provides the lowest loss rate to  $C_0$ . In Figure 5.16 (b), when the load is not heavy, class  $C_1$  experiences the highest loss rate with OPG-NC, and the FPG scheme with different priority group combinations provides the lowest loss rates to  $C_1$ .

However, when the load is heavy, OPG-NC provides the lowest loss rate to  $C_1$  and the FPG scheme makes  $C_1$  experience high loss rate, since OPG-NC makes  $C_0$  suffer from high loss rate. We also notice that in Figure 5.16 (a), the  $C_0$  loss rate increases fast with the OPG-NC scheme when the load is heavy, because the OPG-NC scheme does not necessarily assign the flows of class  $C_0$  to the high priority-groups. In Figure 5.16(c), we observe that both of the OPG schemes provide lower loss rate for the BE class ( $C_2$ ) than the FPG scheme. As we expect, OPG-NC makes class  $C_2$  experience a loss rate lower than OPG-SC does.

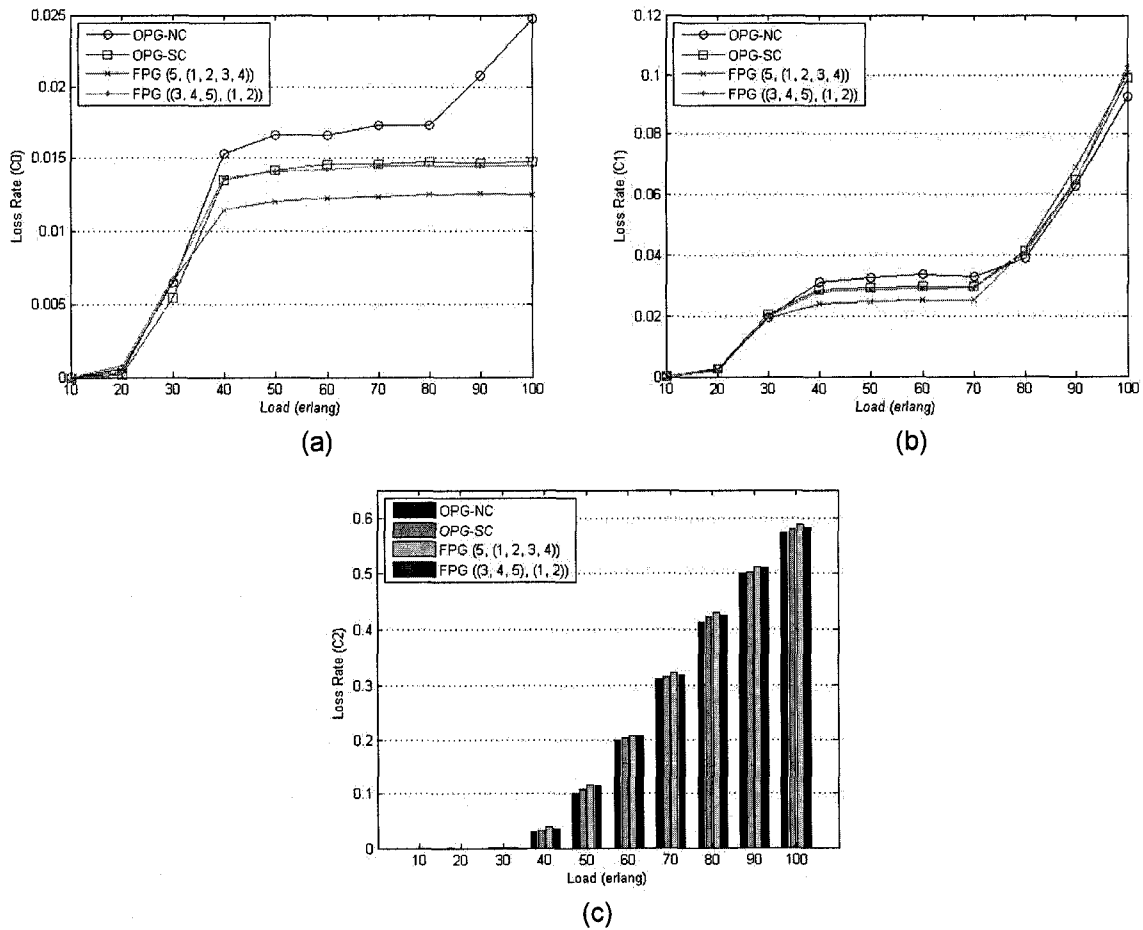


Figure 5.16 Performance Comparison of OPG-SC and OPG-NC on Link  $l_{1,3}$

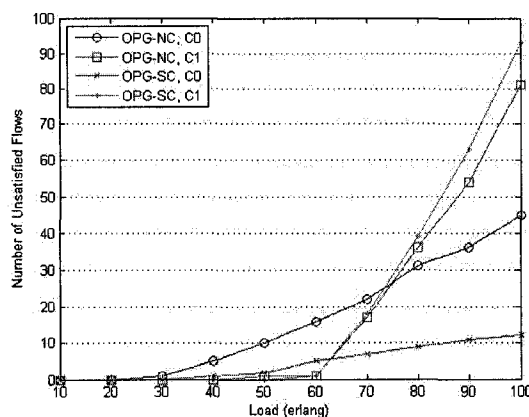


Figure 5.17 Number of Unsatisfied Flows of OPG-SC and OPG-NC

Although OPG-NC provides the BE class with lower loss rates than OPG-SC does, it makes more flows of  $C_0$  class unsatisfied than the OPG-SC scheme, as shown in Figure 5.17. This is because that OPG-NC assigns some  $C_0$  flows to lower priority groups while some  $C_1$  flows are assigned to higher priority groups.

### 5.3.3 Performance of Self-Adaptive Algorithm

Simulations are conducted to evaluate the performance of the proposed self-adaptive algorithm, which integrates the mechanisms of PLU and PLD. We conduct simulations to demonstrate how the integrated self-adaptive algorithm outperforms PLU and PLD to cope with load-unbalance problem. Also, we demonstrate how the integrated algorithm response to traffic-fluctuation. The simulations are conducted in both an OPG-SC-based system and an OPG-NC-based system, in order to evaluate the performance of the self-adaptive algorithm in the two systems respectively.

### 5.3.3.1 Performance of PLU, PLD and Integrated Self-Adaptive Algorithm

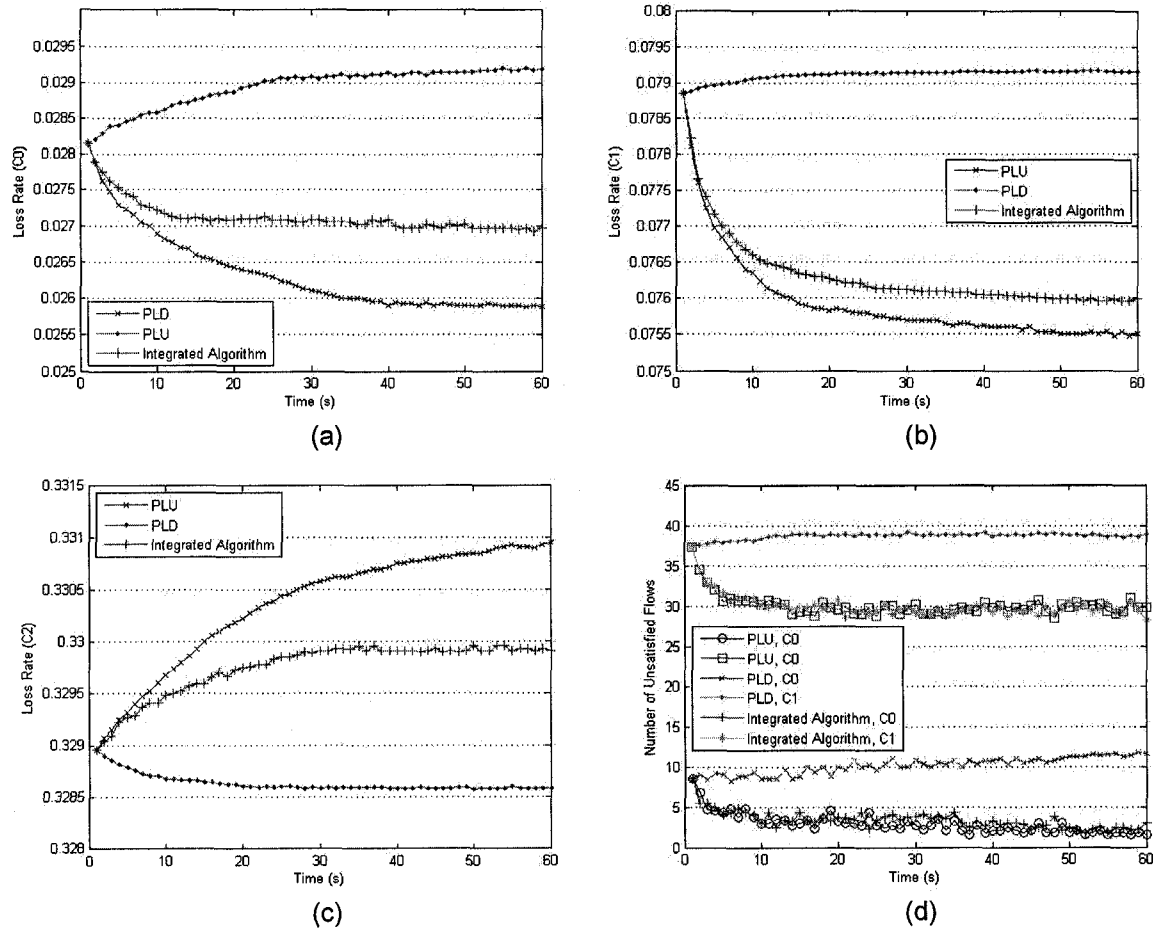


Figure 5.18 Performance of PLU, PLD and Integrated Algorithm in an OPG-SC-Based System

Figure 5.18 compares PLD, PLU and the integrated self-adaptive algorithm based in an OPG-SC-based system. We can observe that the PLU mechanism lowers the loss rates of class  $C_0$  (Figure 5.18 (a)) and class  $C_1$  (Figure 5.18 (b)) and increases the loss rate of the BE class (Figure 5.18 (c)). As a result, as shown in Figure 5.18(d), the PLU mechanism makes fewer unsatisfied flows of the PG classes ( $C_0$  and  $C_1$ ). The PLD mechanism makes the loss

rates of class  $C_0$  and class  $C_1$  increased and lowers the loss rate of the BE class  $C_2$ . Therefore, the numbers of unsatisfied flows of class  $C_0$  and class  $C_1$  increase. The integrated algorithm combines the advantages of the two mechanisms. In Figure 5.18(a) and (b), the loss rates of  $C_0$  and  $C_1$  are lowered down with the integrated algorithm, but not as low as that with the pure PLU mechanism. Thus, as shown in Figure 5.18(d), the unsatisfied flow number of each PG class is reduced as the pure PLU mechanism does. As a tradeoff, the loss rate of the BE class is increased in Figure 5.18 (c), but the integrated algorithm does not make the loss rate of the BE class as high as the pure PLU mechanism does. Therefore, the integrated algorithm achieves a balance of reducing the number of unsatisfied PG flows and keeping the loss rate of the BE class as low as possible.

Figure 5.19 shows the comparison of PLD, PLU and the integrated self-adaptive algorithm in an OPG-NC-based system. Similar to that in Figure 5.18, PLU reduces the loss rates (in Figure 5.19(a) and (b)) and the numbers of unsatisfied flows (Figure 5.19 (d)) of the PG classes and increases the loss rate of the BE class traffic (Figure 5.19 (c)). On the contrary, PLD increases the loss rates (in Figure 5.19(a) and (b)) and the numbers of unsatisfied PG flows (Figure 5.19 (d)) while reducing the loss rate of the BE class traffic (Figure 5.19 (c)). The integrated algorithm lowered down the loss rates of the PG classes (in Figure 5.19(a) and (b)), and thus, reduces the number of unsatisfied PG flows (Figure 5.19 (d)). The loss rate of the BE class is increased, but it is lower than that with the pure PLU mechanism (Figure 5.19 (c)).

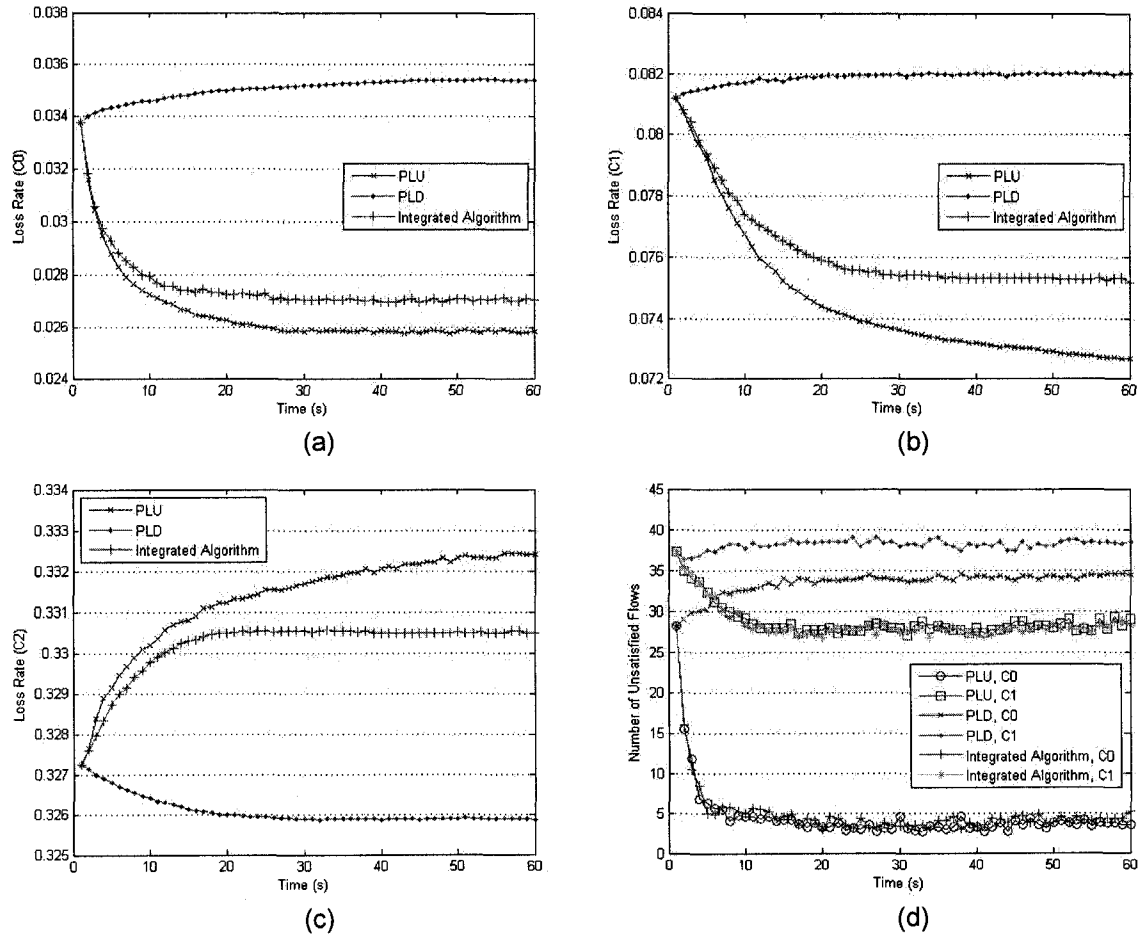


Figure 5.19 Performance of PLU, PLD and Integrated Algorithm in an OPG-NC-Based System

### 5.3.3.2 Self-Adaptive Algorithm Response to Traffic Fluctuation

To demonstrate that the integrated self-adaptive algorithm can handle traffic fluctuation, we conduct simulations based on both the OPG-SC and the OPG-NC schemes. We assume that the load is 80 erlang during the first 60 seconds, and then it jumps to 90 erlang at the 60<sup>th</sup> second. At the 120<sup>th</sup> second, the load drops down to 70 erlang. After that, the load is kept at 70 erlang to the end of the simulations.

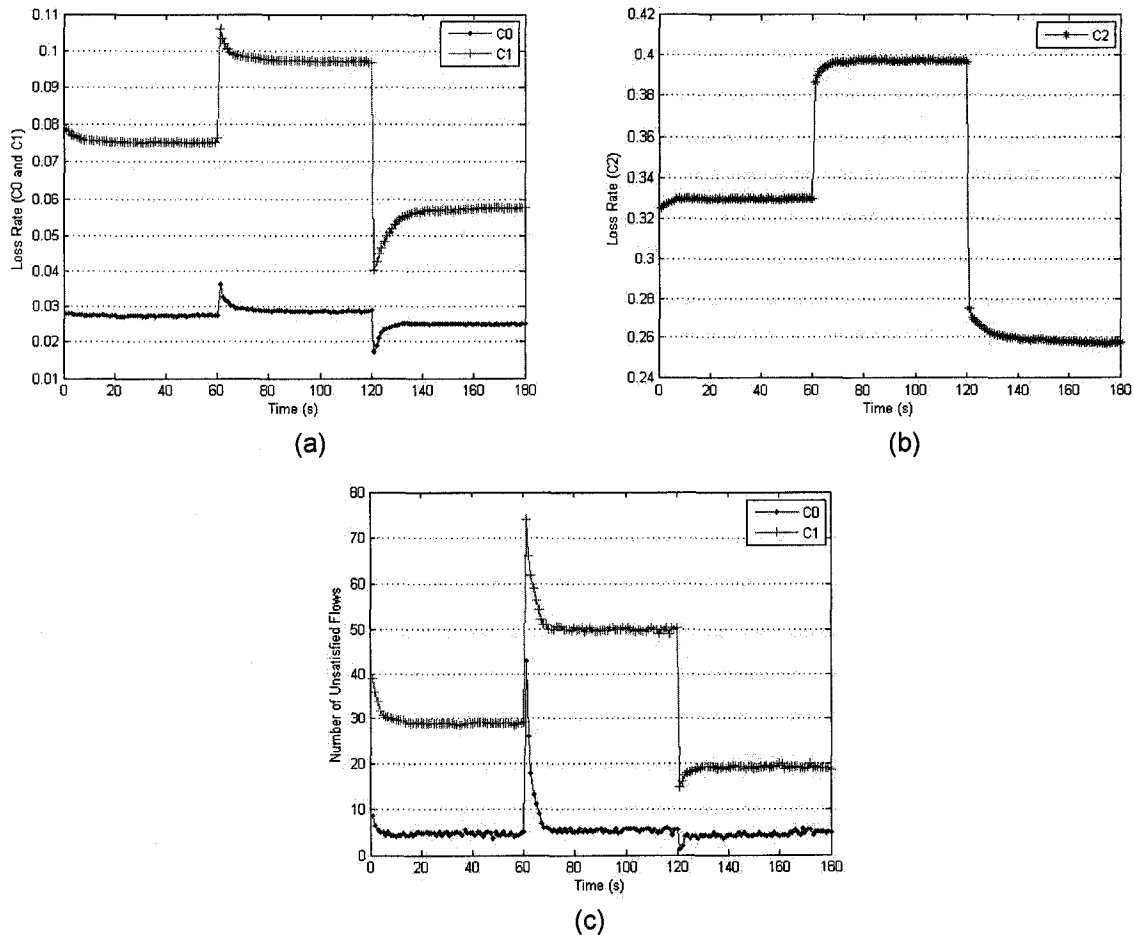


Figure 5.20 Self-Adaptive Algorithm Response to Traffic Fluctuation in an OPG-SC-Based System

Figure 5.20 shows the performance of the self-adaptive algorithm based on the OPG-SC scheme. We observe that the loss rate of each class changes as the traffic load changes. When the simulation begins, the loss rate of each PG class decreases to a stable level (Figure 5.20 (a)), and the number of unsatisfied flows of each PG class reduces to a stable level too (Figure 5.20 (c)). The reason is that at the beginning of the simulation, the integrated self-adaptive algorithm tries to handle the load-unbalance problem in the OBS network, which cannot be handled by either of the OPG schemes. If the priority-level of an unsatisfied

flow cannot be upgraded on bottleneck links, the PLU mechanism can take effect on some light-loaded links, and thus the E2E loss rate of the unsatisfied flow can be reduced, and some of the unsatisfied flows could become satisfied flows. What we need to point out is that when the load is increased from 80 erlang to 90 erlang at the 60<sup>th</sup> second, the loss rate and the number of unsatisfied flows of each PG class jump up first, and then slowly decline to stable levels (Figure 5.20 (a) and (c)). This is because before the load increases, some PG flows were assigned to lower priority groups, which result in a higher loss rates and more unsatisfied PG flows. Then the integrated self-adaptive algorithm makes the loss rate and the number of the unsatisfied flows of each PG class to lower down. On the contrary, when the load dropped from 90 erlang to 70 erlang, the loss rate (shown in Figure 5.20 (a)) and the number of the unsatisfied flows (shown in Figure 5.20 (c)) of each PG class drop to very low levels and then increase to stable levels respectively. The reason is that when the load is decreased from 90 erlang to 70 erlang, the flows of the PG classes are in higher priority groups that make their loss rates and the number of unsatisfied flows relatively low. Then the PLD mechanism works and makes them to be stable on higher levels. In Figure 5.20(b), we can see that the loss rate of the BE class changes with the traffic load as well.

Figure 5.21 shows the performance of the integrated algorithm based on the OPG-NC scheme. Similar to Figure 5.20, at the beginning of the simulation, the loss rate and the number of the unsatisfied flows of each PG classes ( $C_0$  and  $C_1$ ) are decreased. When the load jumps from 80 erlang to 90 erlang at the 60<sup>th</sup> second, the loss rates and the number of the unsatisfied flows of the PG classes jump to higher levels and then slowly drop down. Finally, when the load changes from 90 erlang to 70 erlang, they drop to low levels and then slowly

increase to stable levels. Figure 5.21 (b) shows that the loss rate of the BE class  $C_2$  changes with the load as well.

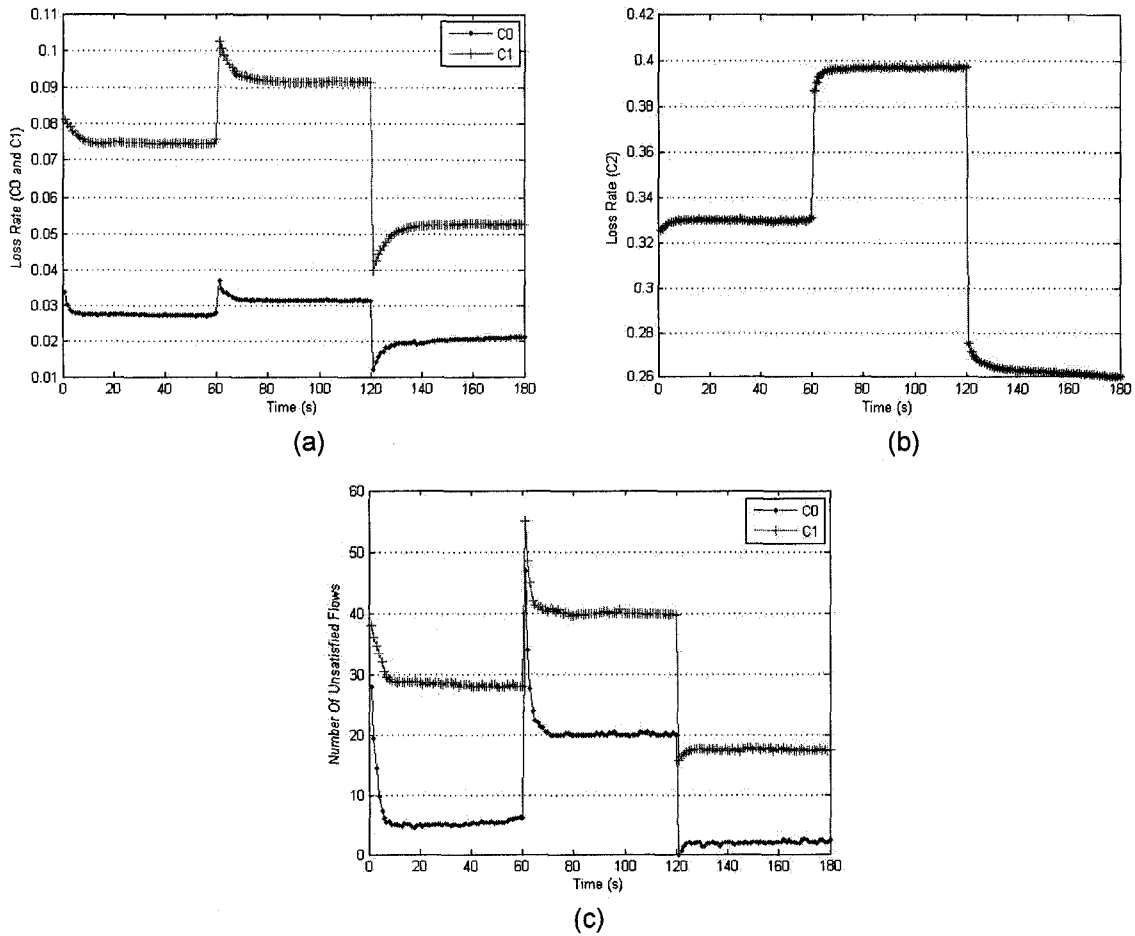


Figure 5.21 Self-Adaptive Algorithm Response to Traffic Fluctuation in an OPG-NC-Based System

Figure 5.22 compares the performance of the integrated self-adaptive algorithm based on OPG-SC to that based on OPG-NC. When the traffic load is not heavy (from the 120<sup>th</sup> second to the 180<sup>th</sup> second, at 70 erlang), the OPG-NC provides lower loss rates for the PG classes  $C_0$  and  $C_1$  (as shown in Figure 5.22(a)), and it provides the BE class with a loss rate that is a little higher than what provided by the OPG-SC (Figure 5.22 (b)). Accordingly, when the load

is 70 erlang, the OPG-NC makes fewer unsatisfied flows of the PG classes, as shown in Figure 5.22(c). The reason is that in an OPG-NC-based system, when the load is not heavy, an unsatisfied flow has more candidate priority-groups to choose than in an OPG-SC-based system. When the load is 80 erlang (during the first 60s period), we can see that the two OPG schemes provide similar performance in terms of loss rate and number of unsatisfied flows. When the load is 90 erlang (from the 60<sup>th</sup> second to the 120<sup>th</sup> second), OPG-NC provides a higher loss rate for class  $C_0$  and a lower loss rate for class  $C_1$  (Figure 5.22(a) and (b)). As a result, OPG-NC makes more flows of class  $C_0$  unsatisfied. However, fewer  $C_1$  flows are unsatisfied with OPG-NC. This is because when the load is heavy, there are fewer chances for the unsatisfied flows to have their priority-levels upgraded successfully, and the OPG-NC scheme cannot guarantee that the flows of  $C_0$  get higher priorities over the flows of  $C_1$ . When the load is heavy (load >70 erlang), the two OPG scheme provides similar loss rate for the BE class  $C_2$  (Figure 5.22 (b)).

We have observed that the integrated self-algorithm based on both the two OPG schemes provides similar loss rates for the BE class. Moreover, making as many flows as possible be satisfied of their E2E loss requirements is the first goal of this thesis. Hence, in a network with the integrated self-adaptive algorithm, the OPG-NC scheme is more desirable when the load is not heavy. On the contrary, when the load gets heavy, the OPG-SC scheme provides better performance in terms of the number of unsatisfied flows.

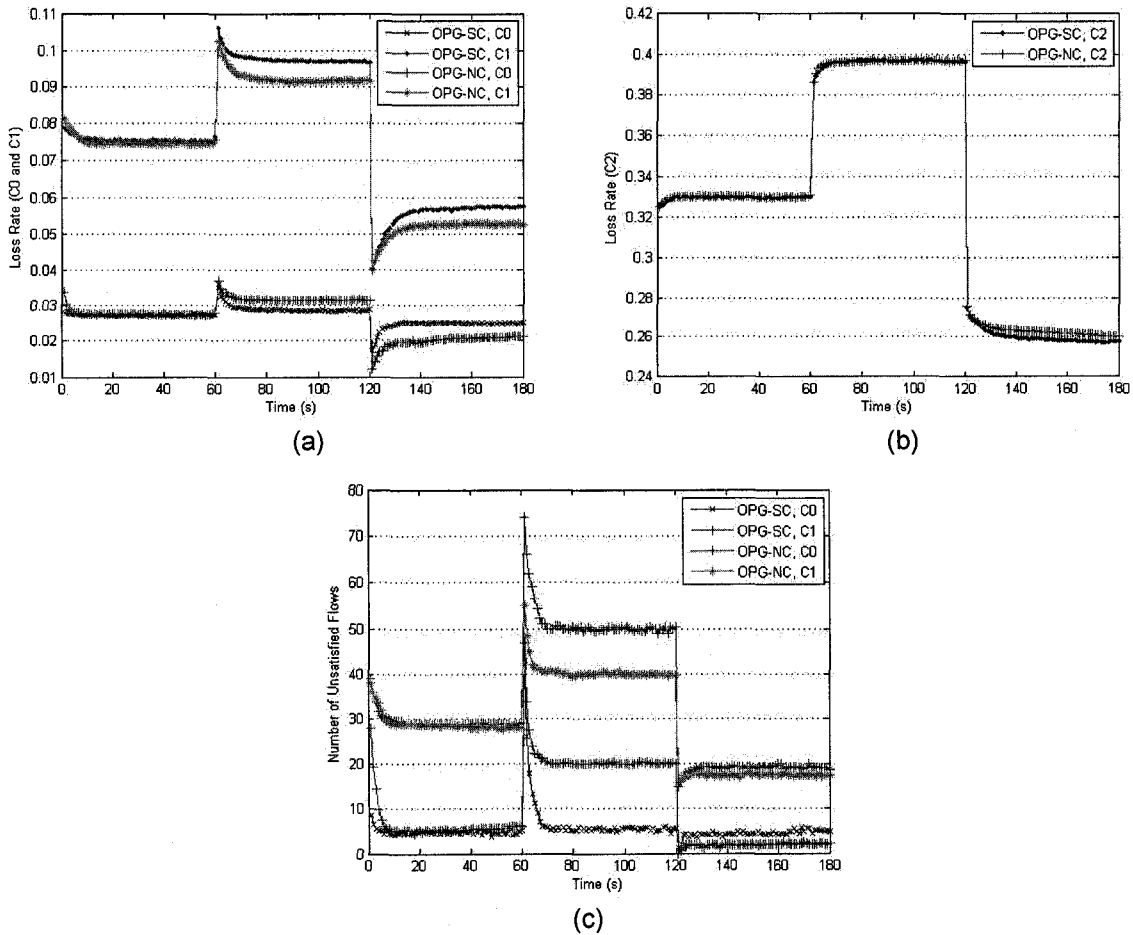


Figure 5.22 Performance Comparison of Self-Adaptive Algorithm in an OPG-SC-Based System and an OPG-NC-Based System

## 5.4 Summary

In this chapter, simulations have been conducted to study the QoS differentiation techniques, which we have proposed in Chapters 3 and 4, on a per-hop basis and an E2E basis respectively.

We have verified the analytical model of our proposed RPS scheme via simulation.

Simulation results have also shown that the proposed RPS scheme outperforms the existing EDS and EDS-DWG schemes in terms of BE class loss rate and bandwidth utilization. We have also compared the proposed BED and BEP mechanisms in the RPS scheme. When the load is not heavy, BEP can reduce the loss rate of the BE class considerably. Furthermore, the proposed SPT and SPG mechanisms are compared as well. From the simulation results, we have observed that SPG can keep the loss rate of each PG class under its threshold with a proper guard-space.

Simulations also have been conducted in a network supporting multiple PG classes in order to validate the proposed per-hop schemes extended from RPS. We have found that RPS-SWG and RPS-DWG overcome the drawback of RPS and can satisfy the loss requirement of the highest priority class. Further, RSP-ESWG and RPS-EDWG can reduce the loss rate of the lower-priority PG class. We have noticed that RPS-DWG and RPS-EDWG outperformed their respective counterparts, RPS-SWG and RPS-ESWG, in terms of loss rates, because of their flexibility on wavelength reservation. Moreover, the ERPS scheme can provide the best performance with easier implementation.

Also, simulations have been carried out over an entire network to validate the proposed optimized priority-grouping schemes and the self-adaptive algorithm. We have first compared the performance of OPG-SC and OPG-NC to that of the existing FPG approach. As we expected, OPG-SC and OPG-NC outperforms FPG in terms of the loss rate of BE class. In addition, OPG-NC can provide lower loss rate for the BE class. However, it makes more unsatisfied flows than OPG-SC does.

The self-adaptive algorithm, which integrates PLU and PLD, can handle the load-unbalance and the traffic-fluctuation problems in networks. In this chapter, we have conducted simulations and compared the performance of the integrated self-adaptive algorithm with that of the pure PLU and the pure PLD mechanisms in both an OPG-SC-based network and an OPG-NC-based network. We have found that in both networks, the integrated self-adaptive algorithm can combine the advantages of PLU and PLD and reduce the number of unsatisfied flows of each PG class while not sacrificing the loss rate of the BE class as much as the pure PLU mechanism does. In addition, we have compared the performance of the integrated self-adaptive algorithm in an OPG-NC-based network to that in an OPG-SC-based network. We have observed that the integrated algorithm can guarantee more flows of their loss rates when the load is not heavy in the OPG-NC-based network; however, when the load is heavy, the OPG-SC-based network performs better in terms of number of unsatisfied flows.

# Chapter 6

## Conclusions and Future Work

### 6.1 Conclusions

This Thesis aims at providing absolute QoS differentiation in OBS networks. While providing loss rate guarantees to PG class flows, we aim at providing the BE class traffic a loss rate that is as low as possible.

We have first presented a per-hop QoS differentiation scheme, which is called Reserve-and-Preempt Scheme (RPS). An analytical model of the RPS scheme has been presented. In order to satisfy the loss requirements of the highest-priority classes when the traffic load is too heavy for the system to provide loss rate guarantees for all of the PG classes, the RPS scheme has been integrated with static wavelength grouping (SWG) scheme and dynamic wavelength grouping (DWG) scheme respectively, and we have proposed the

schemes of RPS-SWG and RPS-DWG. Further, to lower the loss rates of the lower-priority PG classes, we have extended the RPS-SWG and the RPS-DWG schemes, and presented the RPS-ESWG and the RPS-EDWG schemes, in which the lower-priority PG classes are allowed to share the spare bandwidth in the wavelength groups assigned to the higher-priority PG classes. RPS-EDWG outperforms RPS-ESWG because of its flexibility on wavelength reservation. Finally, the Extended Reserve-and-Preempt Scheme (ERPS) has been proposed, which is easier to implement and can provide the best performance.

To provide E2E QoS differentiation, we have applied the ERPS scheme over an entire OBE network. Based on linear programming, we have presented two novel priority-grouping techniques – Optimized Priority Grouping with Single-Class Constraint (OPG-SC) and Optimized Priority Grouping without Single-Class Constraint (OPT-NC). While keeping the loss rates of the PG classes below their loss thresholds, the two proposed techniques aim at reducing the bandwidth consumed by the PG class flows, and thus, the saved bandwidth can be utilized by the BE class traffic. Moreover, we have presented a self-adaptive algorithm, which integrated two mechanisms: Priority-Level Upgrading (PLU) and Priority-Level Degrading (PLD). By upgrading the priority-levels of the unsatisfied PG flows, the PLU mechanism can reduce their loss rates and make them become satisfied PG flows. On the contrary, by degrading the priority-level of the satisfied PG flows whose E2E loss rate are much lower than their E2E loss thresholds, the PLD mechanism can reduce the bandwidth consumption of the satisfied PG flows and the saved bandwidth can be utilized by the the BE class traffic.

We have conducted a simulation study to verify the analytical model of the RPS scheme. The numerical results have shown the correctness of our analytical model. We have also compared the performance of the RPS scheme to that of EDS and EDS-DWG, which are existing per-hop QoS schemes. Simulation results have shown that the proposed RPS scheme considerably outperforms EDS and EDS-DWG in terms of BE class loss rate and bandwidth utilization. We have also compared the proposed schemes of RPS, RPS-SWG, RPS-DWG, RPS-ESWG, RPS-EDWG and ERPS. We have found that RPS-SWG and RPS-DWG can guarantee the loss rate of the highest-priority PG class even when the traffic load is heavy. With RPS-ESWG and RPS-EDWG, the loss rate of the lower-priority PG class can be reduced under heavy load while the highest-priority class is guaranteed its loss rate. We have also found that RPS-EDWG outperforms RPS-ESWG because of the flexibility of dynamic wavelength grouping. Further, the ERPS scheme can provide the best performance with simpler implementation.

Regarding E2E QoS differentiation, we have compared the proposed optimized priority grouping schemes. Simulation results have shown that OPT-NC outperforms OPT-SC in terms of the loss rate of the BE class. However, OPT-SC can make more flows be satisfied than OPT-NC. The self-adaptive algorithm has been studied comprehensively as well. We have found that the PLU mechanism can reduce the number of unsatisfied flows in an OBS network at the expense of the loss rate of the BE class traffic. On the contrary, the PLD mechanism reduces the loss rate of the BE class, but the number of unsatisfied PG flows is increased. By integrating the PLU and the PLD, the self-adaptive algorithm can make the number of unsatisfied flows reduced without much expense on the loss rate of BE class. We

have also observed that the integrated self-adaptive algorithm can guarantee the loss rates of more flows when the load is not heavy in the OPG-NC based network; however, when the load is heavy, the OPG-SC based network performs better in terms of the number of unsatisfied flows of the high-priority class.

## **6.2 Future Work**

The ultimate goal of this thesis is to provide E2E QoS differentiation over an entire OBS network. To implement E2E QoS differentiation, we have applied the proposed ERPS scheme on every core node. At every core node, flows are assigned to different priority-groups according to their per-hop loss thresholds, which are determined not only by their E2E loss requirements, but also by their hop-distances. Therefore, suppose there are two flows belonging to the same service class, the flow with longer hop-distance will be assigned to a higher priority-group than another flow with shorter hop-distance. In addition, with the ERPS scheme, the loss requirements of the higher priority-groups can be guaranteed at the expense of the lower priority-groups when the load is too heavy to satisfy the loss requirements of all priority-groups. Therefore, flows with shorter hop-distances suffer from higher loss rates than those with longer hop-distances. As a result, more flows with shorter hop-distances cannot be satisfied of their E2E loss requirements. This results in unfairness problem. How to solve the unfairness problem is an important research area in the future.

Moreover, QoS differentiation metrics in networks include loss rate, delay, jitter, and so on. This thesis studied only loss rate guarantee, which mainly concerns the core nodes in

OBS networks. In the future, we need to study delay and jitter, which are important parameters for applications such as VoIP and Video Conferencing. In most OBS networks, there are no buffers in the core nodes and data are transferred through the core nodes transparently. As a result, in the core nodes, the delay between a source-destination pair is only the propagation delay, which is determined by the physical distance between the source and the destination. Therefore, delay in OBS networks mainly concerns edge nodes. To study delay and jitter in OBS networks, we need to study assembling mechanisms and offset-time setup at the edge nodes in detail.

## Appendix A:

### Confidence Intervals

When we run a simulation program, we may get a different result each time because the simulation results  $(X_1, \dots, X_n)$  vary depending on the random number seeds used in different runs. We can use the sample mean to be an estimate of the true mean (population mean)  $E(X)$ . The sample mean estimator  $M_n$  provide us with a single value for the estimate of  $E(X) = \mu$ , namely,

$$M_n = \frac{1}{n} \sum_{i=1}^n X_i. \quad (\text{A.1})$$

However, we are not only interested in finding the estimate for the mean, but also determining how accurate the estimate provided by  $M_n$  is. For a particular sample of observations  $X = (X_1, \dots, X_n)$ , we can have the sample variance, which is the average

dispersion about  $M_n$ :

$$V_n^2 = \frac{1}{n-1} \sum_{i=1}^n (X_i - M_n)^2. \quad (\text{A.2})$$

If  $V_n^2$  is small, then the observations are tightly clustered about  $M_n$ , and we can be confident that  $M_n$  is close to  $E(X)$ . However, if  $V_n^2$  is large, the samples are widely dispersed about  $M_n$  and we cannot be confident that  $M_n$  is close to  $E(X)$ .

Instead of seeking a single value to be the “estimate” of the parameter of interest, we can have a different way to approach the question with confidence interval, which is an interval of values that is highly likely to contain the true value of the parameter. Confidence interval can be used to judge the accuracy of an estimate. Suppose we are given a probability  $1 - \alpha$ , and need to find an interval  $[L(X), U(X)]$  such that

$$P[L(X) \leq \mu \leq U(X)] = 1 - \alpha, \quad (\text{A.3})$$

that is, the interval contains the true value of the parameter with probability  $1 - \alpha$ . We say that this interval is a  $(1 - \alpha) \times 100\%$  confidence interval, and  $1 - \alpha$  is called confidence level. The width of a confidence interval is a measure of accuracy with which we can pinpoint the estimate of a parameter. The confidence level provides us a degree of confidence, with which the interval contains the desired parameter. The narrower the confidence interval, the more accurately we can specify the estimate for a parameter.

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*Appendix A: Confidence Intervals*

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Suppose  $X_i$ 's are Gaussian random variables with unknown mean  $\mu$  and known standard deviation  $\sigma$ ,  $M_n$  is then a Gaussian random variable with mean  $\mu$  and variance  $\sigma^2$ . In this case, a  $(1-\alpha)\times 100\%$  confidence interval is given by

$$(M_n - z_{\alpha/2}\sigma/\sqrt{n}, M_n + z_{\alpha/2}\sigma/\sqrt{n}). \quad (\text{A.4})$$

When we do a simulation, we know that the simulation results are independent from each other and follow a normal distribution. However, we do not know the standard deviation  $\sigma$  of the simulation results. The use of  $V_n$  to replace  $\sigma$  is not that accurate. The smaller the sample size the worse the approximation will be. Hence, we can expect that some adjustment will be made based on the sample size. The adjustment we make is that we do not use the normal curve for this approximation. Instead, we use the Student's t-distribution that is based on the sample size. The Student's t-distribution looks like the normal distribution, but as the sample size decreases, it spreads out. For a large sample size  $n$ , it nearly matches the normal distribution. We say that the distribution has  $n-1$  degrees of freedom. To calculate confidence interval, we proceed as before, but we change the table for the value of  $z_{\alpha/2}$  that we use. The  $(1-\alpha)\times 100\%$  confidence interval for the mean  $\mu$  is given by

$$(M_n - z_{\alpha/2, n-1}V_n/\sqrt{n}, M_n + z_{\alpha/2, n-1}V_n/\sqrt{n}). \quad (\text{A.5})$$

The values of  $z_{\alpha/2, n-1}$  for calculating confidence intervals are shown in Table A.1.

*Appendix A: Confidence Intervals*

Table A.1. Values of  $z_{\alpha/2, n-1}$  for Calculating Confidence Intervals

Freedom Degree ( $n - 1$ )	Confidence Level ( $1 - \alpha$ )		
	0.90	0.95	0.99
1	6.314	12.706	63.657
2	2.920	4.303	9.925
3	2.353	3.182	5.841
4	2.132	2.776	4.604
5	2.015	2.571	4.032
6	1.943	2.447	3.707
7	1.895	2.365	3.499
8	1.860	2.306	3.355
9	1.833	2.262	3.250
10	1.812	2.228	3.169
15	1.753	2.131	2.947
20	1.725	2.086	2.845
30	1.697	2.042	2.750
40	1.684	2.021	2.704
60	1.671	2.000	2.660
$\infty$	1.645	1.960	2.576

Table A.2 shows an example of how the confidence intervals are calculated. The example is based on the loss rate of the BE class traffic in a RPS-based OBS network. It has been plotted in Figure 5.2(b). In this example, the 95% confidence intervals are calculated based on 5 independent runs. From the 5 simulation results ( $X_1, X_2, \dots, X_5$ ), we can get the sample mean  $M_n$  and the sample standard deviation  $V_n$  using (A.1) and (A.2) respectively. From Table A.1, we know that the value of  $z_{\alpha/2, n-1}$  is 2.776, because the confidence level is 95% and the freedom degree is 4. Therefore, we can calculate the lower bound  $L(X)$  and the upper bound  $U(X)$  of the confidence interval using (A.5).

In this thesis, each per-hop QoS differentiation simulation has been run 5 times, and each E2E QoS differentiation simulation has been run 10 times. We have calculated the 95%

*Appendix A: Confidence Intervals*

confidence interval on each of the simulations. Since the confidence intervals are too small, we have not plotted them in the figures in Chapter 5.

Table A.2 Example of Confidence Interval Calculations

Load	Simulation Results					$M_n$	$V_n$	$L(X)$	$U(X)$
	$X_1$	$X_2$	$X_3$	$X_4$	$X_5$				
0.3	0	0	1.4E-06	1.4E-06	1.4E-06	8.6E-07	7.8E-07	-1E-07	1.8E-06
0.35	3.0E-05	3.9E-05	3.3E-05	2.0E-05	2.4E-05	2.9E-05	7.2E-06	2E-05	3.8E-05
0.4	5.7E-04	5.9E-04	4.9E-04	5.0E-04	5.6E-04	0.00054	4.6E-05	0.00048	0.0006
0.45	0.00216	0.00211	0.00221	0.00235	0.00211	0.00219	0.0001	0.00206	0.00231
0.5	0.00568	0.0057	0.00612	0.00608	0.00591	0.0059	0.00021	0.00564	0.00616
0.55	0.01291	0.01291	0.01289	0.01295	0.0129	0.01291	2.3E-05	0.01288	0.01294
0.6	0.02387	0.024	0.02395	0.02405	0.02406	0.02398	7.7E-05	0.02389	0.02408
0.65	0.04007	0.03992	0.03993	0.04035	0.03983	0.04002	0.0002	0.03977	0.04027
0.7	0.06063	0.06042	0.06006	0.06107	0.06069	0.06057	0.00037	0.06012	0.06103
0.75	0.08551	0.08603	0.08683	0.08613	0.08497	0.08589	0.0007	0.08503	0.08676
0.8	0.11424	0.1138	0.11367	0.11544	0.11494	0.11442	0.00076	0.11348	0.11536
0.85	0.14669	0.14647	0.14605	0.1479	0.14625	0.14667	0.00073	0.14577	0.14757
0.9	0.17984	0.17998	0.17886	0.18082	0.17978	0.17986	0.0007	0.17899	0.18072
0.95	0.21424	0.21483	0.21387	0.21556	0.21471	0.21464	0.00064	0.21385	0.21544
1	0.25055	0.25012	0.24927	0.252	0.25052	0.25049	0.00099	0.24926	0.25172

# Bibliography

- [ARO02] A. Arora and S. Subramaniam, "Wavelength Conversion Placement in WDM Mesh Optical Networks," *Photonic Network Communications*, Vol. 4, No. 2, pp. 167-177, May 2002.
- [BAL02] I. Baldine, H. G. Perros, G. N. Rouskas and D. Stevenson, "JumpStart: A Just-in-time Signaling Architecture for WDM Burst-Switched Networks," *IEEE Communications Magazine*, Vol. 40, No. 2, pp. 82-89, Feb. 2002.
- [BAR04] N. Barakat and E. H. Sargent, "Qualifying the Effect of Extended Offsets in Optical Burst Switching Networks," in *Proc. IEEE Canadian Conference on Electrical and Computer Engineering (CCECE 2004)*, pp. 2331-2335, May 2004.
- [BAR05] N. Barakat, E. H. Sargent, "Analytical Modeling of Offset-Induced Priority in Multiclass OBS Networks," *IEEE Transactions on Communications*, Vol.53, No. 8, pp. 1343-1352, Aug. 2005
- [BLU01] D. J. Blumenthal, "Photonic Packet Switching and Optical Label Swapping,"

## *Bibliography*

---

*Optical Networks Magazine*, pp. 1-12, Nov.-Dec. 2001.

- [BLU03] D. J. Blumenthal, J. E. Bowers, L. Rau, H.-F. Chou, S. Ranngarajan, W. Wang, and H. N. Poulsen, "Optical signal processing for optical packet switching networks," *IEEE Optical Communications*, pp. S23-S29, Feb. 2003.
- [BOR93] F. Borgonovo, L. Fratta and J. A. Bannister, "Unslotted Deflection Routing in All-optical Networks," in *Proc. IEEE GLOBECOM 1993*, Symposium on Optical Networks, Vol. 1, pp. 119-125, 1993.
- [BOR94] F. Borgonovo, L. Fratta and J. A. Bannister, "On the Design of Optical Deflection-routing Networks," in *Proc. IEEE INFOCOM 1994*, Vol. 1, pp. 120-129, 1994.
- [BRA90] C. Brackett, "Dense Wavelength Division Multiplexing Networks: Principles and Applications," *IEEE Journal on Selected Areas in Communications*, Vol. 8, No. 6, pp. 948-964, Aug. 1990.
- [BRI98] U. Briem, E. Wallmeier, C. Beck and F. Matthiesen, "The Traffic Management for an ATM Switch with Per-VC Queuing: Concept and Implementations," *IEEE Communications Magazine*, Vol. 36, pp. 88-93, January 1998.
- [CAN03] H. C. Cankaya, S. Charcranon, T. S. El-Bawab, "A Preemptive Scheduling Technique for OBS Networks with Service Differentiation," in *proc. IEEE Globecom 2003*, Symposium on Optical Networking, pp. 2704-2708, Nov. 2003.

### *Bibliography*

---

- [CHA99] G.-K. Chang et al., "Low Latency Packet Forwarding in IP over WDM Networks Using Optical Label Switching Techniques," in *Proc. IEEE LEOS 1999 Annual Mtg.*, pp. 17-18, 1999.
- [CHE01] Y. Chen, M. Hamdi and Danny H. K. Tsang, "Proportional QoS over OBS networks," in *Proc. IEEE Globecom 2001*, Vol. 3, pp. 1510-1514, Nov. 2001.
- [CHE03] Y. Chen, H. Wu, D. Xu and C. Qiao, "Performance Analysis of Optical Burst Switched Node with Deflection Routing," in *Proc. IEEE ICC 2003*, Symposium on Optical Networking, Vol. 2, pp. 1355-1359, June 2003.
- [CHE04] Y. Chen, C. Qiao and X. Yu, "Optical burst switching: a new area in optical networking research," *IEEE Network Magazine*, Vol. 18, No. 3, pp. 16-23, May-June 2004.
- [CHL96] I. Chlamtac A. Fumagalli, L. G. Kazovsky et al., "CORD: Contention resolution by delay lines," *IEEE Journal on Selected Areas on Communications*, Vol. 40, No. 3, pp. 80-87, 1996.
- [COU05] T. Coutelen, H. Elbiaze and B. Jaumard, "Performance comparison of OCS and OBS switching paradigms," in *Proc. IEEE 7th International Conference Transparent Optical Networks (ICTON 2005)*, Vol. 1, pp. 212-215, July 2005.
- [CRO97] M. E. Crovella and A. Bestavros, "Self-Similarity in World Wide Web Traffic: Evidence and Possible Causes," *IEEE/ACM Transactions on Networking*, Vol. 5, No.

## *Bibliography*

---

6, pp. 835-846, Dec. 1997.

[DET02a] A. Detti, V. Eramo and M. Listanti, "Optical Burst Switching with Burst Drop (OBD/BD): an Easy OBS Improvement," *in Proc. IEEE ICC 2002*, Vol. 5, pp. 2687-2691, April-May 2002.

[DET02b] A. Detti, V. Eramo, and M. Listanti, "Performance Evaluation of a New Technique for IP Support in a WDM Optical Network: Optical Composite Burst Switching (OCBS)," *IEEE Journal of Lightwave Technology*, Vol. 20, No. 2, pp. 154-165, 2002.

[DET05] M.C.F. De Toledo and W. Zucchi, "Simulation of a optical burst switch using fiber delay lines," *in Proc. IEEE International Conference on Microwave and Optoelectronics*, pp. 334-340, July 2005.

[DHA06] E. Dhavarudha, C. Charoenlarnnoppaparut and S. Runggeratigul, "Performance and Cost Comparison for Optical Burst Switching and Optical Circuit Switching" , *in Proc. 2006 IEEE International Symposium on Communications and Information Technologies (ISCIT 2006)*, pp. 807-811, Oct. 2006.

[DIX03] S. Dixit, "IP over WDM: Building the Next Generation Optical Internet," Wiley-Interscience, 1st edition, Mar. 2003.

[DOV00] C. Dovrolis and P. Ramanathan, "Proportional Differentiated Services, Part II: Loss Rate Differentiation and Packet Dropping," *in IEEE/IFIP International Workshop*

*Bibliography*

---

*on Quality of Service (IWQoS 2000)*, pp. 52-61, June 2000.

- [DOV01] C. Dovrolis and P. Ramanathan, "Dynamic Class Selection: from Relative Differentiation to Absolute QoS," in *Proc. IEEE Ninth International Conference on Network Protocols*, pp. 120-128, Nov. 2001.
- [DOV02] C. Dovrolis, D. Stiliadis and P. Ramanathan, "Proportional Differentiated Services: Delay Differentiation and Packet Scheduling," *IEEE/ACM Transactions on Networking*, Vol. 10, No. 1, pp. 12-26, Feb. 2002.
- [DOV99] C. Dovrolis, D. Stiliadis and P. Ramanathan, "A Case for Relative Differentiated Services and the Proportional Differentiation Model," *IEEE Network Magazine*, Vol. 13, pp. 26-34, Sept.-Oct. 1999.
- [DUS00] M. Duser , E. Kozlovski, R.I. Killey and P. Bayvel, "Design Tradeoffs in Optical Burst Switched Networks with Dynamic Wavelength Allocation," in *Proc. ECOC 2000*, pp. 23-24, 2000.
- [DUS02] M. Duser, and P. Bayvel, "Analysis of Dynamically Wavelength-Routed Optical Burst Switched Networks Architecture," *IEEE Journal of Lightwave Technology*, Vol. 20, No. 4, pp. 574-585, April 2002
- [ELB02] T. El-Bawab and J.-D. Shin, "Optical Packet Switching in Core Networks: Between Vision and Reality," *IEEE Communications Magazine*, Vol. 38, No. 3, pp. 86-92, 2002.

## *Bibliography*

---

- [ELM00] J. M. H. Elmirghani and H. T. Mouftah, "All Optical Wavelength Conversion: Technologies and Applications on DWDM Networks," *IEEE Communications Magazine*, Vol. 38, No. 3, pp. 86-92, March 2000.
- [FEN02] P. Fan, C. Feng, Y. Wang and N. Ge, "Investigation of the Time-Offset Based QoS Support with Optical Burst Switching in WDM Networks," in *Proc. IEEE ICC 200, Symposium on Optical networking*, Vol. 5, pp. 2682-2686, April-May 2002.
- [GHA00] N. Ghani, S. Dixit and T. S. Wang, "On IP-over-WDM Integration," *IEEE Communication Magazine*, Vol. 41, No. 9, pp. 42-45, March 2000.
- [GRI05] D. Griffith, K. Sriram and N. Golmie, "Protection Switching for Optical Bursts Using Segmentation and Deflection Routing," *IEEE Communications Letters*, Vol. 9, No. 10, pp. 930-932, Oct. 2005.
- [HSU02] C. F. Hsu, T. L. Liu and N. F. Huang, "Performance Analysis of Deflection Routing in Optical Burst-Switched Networks," in *Proc. IEEE INFOCOM 2002*, Vol. 1, pp. 66-73, June 2002.
- [HUN98a] D. K. Hunter, W. D. Cornwell, T. H. Gilfedder, A. Frenzen and I. Andonovic, "Buffering in Optical Packet Switches," *IEEE Journal of Lightwave Technology*, Vol. 16, No. 12, pp. 2081-2094, 1998.
- [HUN98b] D. K. Hunter, M. C. Chia and I. Andonovic, "A Wavelength Switched Packet Network," *IEEE Communications Magazine*, Vol. 37, No. 3, pp. 120-129, 1998.

## *Bibliography*

---

- [JAP06] Ministry of Internal Affairs and Communications, Tokyo, Japan, "Main data on information and communication in Japan," [online]. Available: [http://www.soumu.go.jp/joho\\_tsusin/eng/statistics.html/](http://www.soumu.go.jp/joho_tsusin/eng/statistics.html/), Mar. 3, 2006.
- [KAH04] A. Kaheel and H. Alnuweiri, "Quantitative QoS Guarantees in Labeled Optical Burst Switching Networks," in *Proc. IEEE Globecom 2004*, Symposium on Optical Networking, pp. 1747-1753, Nov. 2004
- [KAM04] N. Kamiyama, "Comparison of All-Optical Architectures for Backbone Networks," *IEICE Transactions on Communications*, Vol. E87-B, No. 10, pp. 2877-2885, Oct. 2004.
- [KIM03] S. Kim, K. Min and M. Kang, "Dynamic Wavelength Management Method in OBS Networks," *US. Patent Application 10338243*, Jan. 7, 2003
- [KIM05] S. Kim, J. S. Choi and M. Kang, "Providing Absolute Differentiated Services for Optical Burst Switching Networks: Loss Differentiation," *IEE Proceedings Communications*, Vol. 152, No. 4, pp. 439-446, August 2005.
- [KIR06] P. Kirci and A. H. Zaim, "Comparison of OBS Protocols," in *Proc. IEEE 2006 International Symposium on Computer Networks*, pp. 158-161, June 2006.
- [KOZ01] E. Kozlovski, M. Duser, I. de Miguel and P. Bayvel, "Analysis of Burst Scheduling for Dynamic Wavelength Assignment in Optical Burst-Switched Networks," in *Proc. IEEE The 14th Annual Meeting of the Lasers and Electro-Optics Society (LEOS*

*Bibliography*

---

- 2001), Vol. 1, pp. 161-162, Nov. 2001.
- [LEE03a] G. Lee, B. Wyrowski, M. Zukerman, J. Choi, and C. Foh, "Performance Evaluation of an Optical Hybrid Switching System," in *Proc. IEEE Globecom 2003*, Vol. 22, No. 1, pp. 2508-2512, Dec. 2003.
- [LEE03b] S. Lee, K. Sriram, H. Kim and J. Song, "Contention-Based Limited Deflection Routing in OBS Networks," in *Proc. IEEE Globecom 2003*, pp. 2633-2637, San Francisco, USA, Dec. 2003.
- [LEE05a] Y. G. Lee, N. U. Kim, T. W. Um and M. H. Kang, "Decision of the Fiber Delay Line Length in Optical Burst Switching Networks," in *Proc. IEEE the 7th International Conference on Advanced Communication Technology, (ICACT 2005)*, Vol. 2, pp. 1049-1051, Feb. 2005.
- [LEE05b] S. Lee, K. Sriram, H. Kim and J. Song, "Contention-Based Limited Deflection Routing Protocol in Optical Burst-Switched Networks," *IEEE Journal on Selected Areas in Communications*, Vol. 23, No. 8, pp. 1596-1611, Aug. 2005.
- [LEU01] M. K. H. Leung, J. C. S. Lui and D. K. Y. Yau, "Adaptive Proportional Delay Differentiation Services: Characterization and Performance Evaluation," *IEEE/ACM Transactions on Networking*, Vol. 9, No. 6, pp. 808-817, Dec. 2001.
- [LI03] J. Li and C. Qiao, "Schedule Burst Proactively for Optical Burst Switching Networks," in *Proc. IEEE GLOBECOM 2003*, Symposium on Optical Networking,

## *Bibliography*

---

Vol. 5, pp. 2787-2791, Nov. 2003.

- [LIA04] W. Liao and C.-H. Loi, "Providing Service Differentiation for Optical-Burst-Switched Networks," *IEEE Journal of Lightwave Technology*, Vol. 22, No. 7, pp. 1651-1660, July 2004.
- [LIU03] J. Liu, N. Ansari and T. J. Ott, "FRR for Latency Reduction and QoS Provisioning in OBS Networks," *IEEE Journal on Selected Areas in Communications*, Vol. 21, No. 7, pp. 1210-1219, Sept. 2003.
- [LJO05] M. Ljolje, R. Inkret and B. Mikac, "A Comparative Analysis of Data Scheduling Algorithms in Optical Burst Switching Networks," in *Proc. IEEE Conference on Optical Network Design and Modeling*, pp. 493-500, Feb. 2005.
- [LOI02] C. Loi, W. Liao and D. Yang, "Service Differentiation in Optical Burst Switched Networks," in *Proc. IEEE GLOBECOM 2002*, Symposium on Optical Networking, Vol. 3, pp. 2313-2317, Nov. 2002.
- [LU04] X. Lu and B. L. Mark, "Performance Modeling of Optical-Burst Switching with Fiber Delay Lines," *IEEE Transactions on Communications*, Vol. 52, No. 12, pp. 2175-2183, Dec. 2004.
- [MAL05] S. Malik and U. Killat, "Impact of Burst Aggregation Time on Performance in Optical Burst Switching Networks," in *Proc. 2005 IEEE Conference on Optical Network Design and Modeling*, pp. 19-25. Feb. 2005.

## *Bibliography*

---

- [MAN98] J. Manchester, J. Anderson, B. Doshi, and S. Dravida, "IP over SONET," *IEEE Communications Magazine*, Vol. 36, No. 5, pp. 136-42, May 1998.
- [MAR06] J. Maranhao, A. Soares, and W. Giozza, "Cost Benefit Study of Sparse-Partial Wavelength Conversion Architectures," in *Proc. 2006 IEEE International Conference on Systems and Networks Communication (ICSNC '06)*, pp. 12-12, Oct. 2006.
- [MIG01] I. Miguel, M. Duser and P. Bayvel, "Traffic Load Bound for Optical Burst-switched Networks with Dynamic Wavelength Allocation," in *Proc. IFIP 5<sup>th</sup> Working Conference on Optical Network Design and Modelling (ONDM 2001)*, Feb. 2001
- [MIL90] D. L. Mills et al., "Highball: A High Speed, Reserved-Access, Wide-Area Network," *Tec. Rep. 90-9-3, Elec. Eng. Dep., Univ. of Delaware*, 1990.
- [MOD99] E. Modiano, "WDM-Based Packet Networks," *IEEE Communications Magazine*, Vol. 37, No. 3, pp. 130-35, March 1999.
- [MOR04] D. Morato, E. Magana, M. Izal and J. Aracil, "Approximations for End-to-End Delay Analysis in OBS Networks with Light Load," in *Proc. IEEE 6th International Conference on Transparent Optical Networks (ICTON2004)*, Vol. 1, pp. 243-246, July 2004.
- [MOR05] I. M. Moraes and O. C. M. B. Duarte, "An Efficient Multiclass Mechanism for Optical Burst-Switching Networks," in *Proc. IEEE 2<sup>nd</sup> International Conference on*

## *Bibliography*

---

*Broadband Networks, 2005*, pp. 1083-1092, Oct. 2005.

- [MUR01] C. S. R. Murthy. and M. Guruswamy, "WDM Optical Networks, Concepts, Design, and Algorithms," Prentice Hall India, ISBN-81-203-2129-4, 2001.
- [NAR06] K.V. Narayanaswamy, N.G. Kurahatti and T. Srinivas, "Just-in-time Signaling with Modified Architecture for Optical Burst Switching WDM Networks," *in Proc. IEEE International Conference on Wireless and Optical Communications Networks*, April 2006.
- [NEU03] M. Neuts, Z. Rosberg, H. L. Vu, J. White and M. Zukerman, "Performance Enhancement of Optical Burst Switching Using Burst Segmentation," *in Proc. IEEE ICC 2003*, Symposium on Optical Networking, Vol. 3, pp. 1828-1832, May 2003.
- [NEW97] P. Newman , G. Minshall, T. Lyon and L. Huston, "IP Switching and Gigabit Routers," *IEEE Communications Magazine*, Vol. 35, No. 1, pp. 705-18, Jan. 1997.
- [NGO06] S.-H. Ngo, X. Jian and S. Horiguchi, "Hybrid Deflection and Retransmission Routing Schemes for OBS Networks," *in Proc. 2006 IEEE Workshop on High Performance Switching and Routing (HPSR 2006)*, June 2006
- [ODL03] A. M. Odlyzko, "Internet traffic growth: Sources and implications," *in Proc. SPIE*, Vol. 5247, pp. 1-15, 2003
- [OGI05] N. Ogino and H. Tanaka, "Deflection Routing for Optical Bursts Considering Possibility of Contention at Downstream Nodes," *IEICE Transactions on*

## *Bibliography*

---

- Communications*, Vol. E88-B, No. 9, pp. 3660–3667, Nov. 2005.
- [OMA01] M. J. O’Mahony, D. Simeonidou, D. K. Hunter and A Tzanakaki, “The Application of Optical Packet Switching in Future Communication Networks,” *IEEE Communications Magazine*, Vol. 39, No. 3, pp. 128-135, 2001.
- [PAPA03] G. I. Papadimitriou, C. Papazoglou and A. S. Pomportis, “Optical Switching: Switch Fabrics, Techniques, and Architectures,” *IEEE Journal of Lightwave Technology*, Vol. 21, No. 2, pp. 384-405, Feb. 2003.
- [PED06] J. Pedro, P. Monteiro, and J. Pires, “Wavelength Contention Minimization Strategies for Optical Burst-Switched Networks,” in *Proc. IEEE Globecom 2006*, Symposium on Optical Networking, pp. 1-6, Nov. 2006.
- [PHU04] M. H. Phung, K.C. Chua, G. Mohan, M. Motani, and T. C. Wong, “Absolute QoS Signalling and Reservation in Optical Burst-Switched Networks,” in *Proc. IEEE Globecom 2004*, Symposium on Optical Networking, pp. 2009-2013, Nov. 2004.
- [PHU06] M. H. Phung, K.C. Chua, G. Mohan, M. Motani, and T. C. Wong, “An Absolute QoS Framework for Loss Guarantees in Optical Burst-Switched Networks,” *IEEE Transactions on Communications*, Vol. 55, No. 6, pp. 1191-1200, June 2007.
- [PHU07] J. Phuritakul, Y. Ji and S. Yamada, “Proactive Wavelength Pre-Emption for Supporting Absolute QoS in Optical-Burst-Switched Networks”, *IEEE Journal of Lightwave Technology*, Vol. 25, No. 5, pp. 1130-1137, May 2007.

## *Bibliography*

---

- [POP02] F. Poppe, K. Laevens, H. Michiel and S. Molenaar, "Quality-of-Service Differentiation and Fairness in Optical Burst-Switched Networks," *in SPIE Proc. Optical Networking and Communications (Opticomm 2002)*, Vol. 4874, pp. 118-124, 2002.
- [QIA00a] C. Qiao and M. Yoo, "Choices, Features and Issues in Optical Burst Switching," *SPIE Optical Network Magazine*, Vol. 1, No. 2, pp. 36-44, 2000.
- [QIA00b] C. Qiao. "Labeled Optical Burst Switching for IP-over-WDM Integration," *IEEE Communications Magazine*, Vol. 38, No. 9, pp. 104-114, Sept. 2000.
- [QIA03] C. Qiao, Y. Chen and J. Staley, "The Potentials of Optical Burst Switching (OBS)," *in Proc. 2003 IEEE Optical Fiber Communications Conference (OFC 2003)*, Vol. 1, pp. 219-220, March 2003.
- [QIA99a] C. Qiao and M. Yoo, "Optical Burst Switching (OBS) - a New Paradigm for an Optical Internet," *IOS Journal of High Speed Networks*, Vol. 8, No. 1, pp. 69-84, 1999.
- [QIA99b] C. Qiao, M. Jeong, A. Guha, X. Zhang and J. Wei, "WDM Multicasting in IP Over WDM Networks," *in Proc. 7<sup>th</sup> IEEE International Conference on Network Protocols (ICNP1999)*, pp. 89-96, 1999.
- [RAM03] J. Ramamirtham and J. Turner, "Time Sliced Optical Burst Switching," *in Proc. IEEE INFOCOM 2003*, Vol. 3, pp. 2030-2038, March-April 2003.

## *Bibliography*

---

- [RAM98] B. Ramamurthy and B. Mukherjee, "Wavelength Conversion in WDM Networking," *IEEE Journal of Selected Areas in Communications*, Vol. 16, No. 7, pp. 1061-1073, 1998.
- [ROS03] Z. Rosberg, H.L. Vu and M. Zukerman, "Burst Segmentation Benefit in Optical Switching," *IEEE Communications Letters*, Vol. 7, No. 3, pp. 127-129, March 2003.
- [ROS06] Z. Rosberg, A. Zalesky, H.L. Vu and M. Zukerman, "Analysis of OBS Networks With Limited Wavelength Conversion" *IEEE/ACM Transactions on Networking*, Vol. 14, No. 5, pp. 1118-1127, Oct. 2006.
- [SRI03] K. Sriram, D. W. Griffith, S. Lee and N. T. Golmie, "Optical Burst Switching: Benefits and Challenges," in *Proc. 2003 IEEE International Workshop on Optical Burst/Packet Switching (WOBS 2003)*, Oct. 2003
- [STA07] W. Stallings, "Data and Computer Communications," Pearson Education, Inc., 7<sup>th</sup> Edition, 2007.
- [SUN05] Y.Sun, I.Sheriff, E.M.Belding, K.C.Almeroth, "An Experimental Study of Multimedia Traffic Performance in Mesh Networks," in *Proc. 2005 IEEE International Workshop on Wireless Traffic Measurements and Modeling*, pp. 25-30, 2005.
- [TAN00] L. Tancevski, S. Yegananarayanan, G. Castagnon, L. Tamil, F. Masetti and T. McDermott, "Optical Routing of Asynchronous Variable Length Packets," *IEEE*

## *Bibliography*

---

- Journal on Selected Areas in Communications*, Vol. 18, No. 10, pp. 2084-1093, 2000.
- [TAN04] C.-W. Tan, M. Gurusamy and J. C.-S. Lui, "Achieving Proportional Loss Differentiation Using Probabilistic Preemptive Burst Segmentation in Optical Burst Switching WDM Networks," in *Proc. IEEE Globecom 2004*, Symposium on Optical Networking, pp. 1754-1758, Nov. 2004
- [TAN06] C.-W. Tan, M. Gurusamy and J. C.-S. Lui, "Achieving Multi-Class Service Differentiation in WDM Optical Burst Switching Networks: A Probabilistic Preemptive Burst Segmentation Scheme," *IEEE Journal of Selected Areas in Communications*, Vol. 24, No. 12, pp. 106-119, Dec. 2006.
- [TEN04a] J. Teng and G. N. Rouskas, "On Wavelength Assignment in Optical Burst Switched Networks," in *Proc. IEEE First International Conference on Broadband Networks (BROADNETS'04)*, pp. 24-33, 2004.
- [TEN04b] J. Teng and G. N. Rouskas, "A Detailed Analysis and Performance Comparison of Wavelength Reservation Schemes for Optical Burst Switched Networks," *Kluwer Photonic Network Communications*, Vol. 9, No. 3, pp. 311-335, 2004.
- [TRI00] T. Tripathi and K. N. Sivarajan, "Computing Approximate Blocking Probabilities in Wavelength Routed All-Optical Networks with Limited Range Wavelength Conversion," *IEEE Journal of Selected Areas in Communications*, Vol. 18, No. 10, pp. 2123-2129, Oct. 2000.

*Bibliography*

---

- [TSA00] V. Tsaoussidis and S. Wei, "QoS Management at the Transport Layer," in *Proc. 2000 IEEE International Conference on Information Technology: Coding and Computing (ITC 2000)*, pp. 312-317, 2000.
- [TUR00] J. Turner, "WDM burst switching for Petabit data networks," in *Proc. 2000 IEEE Optical Fiber Communications Conference (OFC 2000)*, Vol. 2, pp. 47-49, Mar. 2000.
- [TUR99] J. Turner, "Terabit burst switching," *IEEE Journal of High Speed Networks*, Vol. 8, No. 1, pp. 3-16, 1999.
- [VAR97] E. Vararigos and V. Sharma, "The Ready-To-Go Virtual Circuit Protocol: A Loss-Free Protocol for Multigigabit Networks Using FIFO Buffers," *IEEE/ACM Transactions on Networking*, Vol. 5, No. 5, pp. 705-18, Oct. 1997.
- [VER97] A. Verma and D. Stilladis, "Hardware Implementation of Fair Queueing Algorithms for Asynchronous Transfer Node Networks," *IEEE Communications Magazine*, Vol. 35, pp. 74-80, Dec. 1997.
- [VIS98] A. Viswanathan, N. Feldman, Z. Wang and R. Callon, "Evolution of Multiprotocol Label Switching," *IEEE Communications Magazine*, Vol. 36, No. 5, pp. 165-73, May 1998.
- [VOK02a] V. Vokkarane, J.P. Jue and S. Sitaraman, "Burst Segmentation: An Approach for Reducing Packet Loss in Optical Burst Switched Networks," in *Proc. IEEE ICC*

## *Bibliography*

---

2002, Symposium on Optical Networking, Vol. 5, pp. 2673-2677, 2002.

- [VOK02b] V. Vokkarane and J.P. Jue, "Prioritized Routing and Burst Segmentation for QoS in Optical Burst-Switched Networks," in *Proc. 2002 IEEE Optical Fiber Communications Conference (OFC 2002)*, pp. 221-222, Mar. 2002.
- [VOK02c] V. Vokkarane, K. Haridoss and J.P. Jue, "Threshold-Based Burst Assembly Policies for QoS Support in Optical Burst-Switched Networks," in *Proc. SPIE Opticomm 2002*, pp. 125-136, 2002.
- [VOK02d] V. Vokkarane, Q. Zhang, J.P. Jue and B. Chen, "Generalized Burst Assembly and Scheduling Techniques for QoS Support to Optical Burst-Switched Networks," in *Proc. IEEE GLOBECOM 2002, Symposium on Optical Networking*, Vol. 3, pp. 2747-2751, 2002.
- [VOK03a] V. M. Vokkarane and J. P. Jue, "Segmentation-Based Non-preemptive Scheduling Algorithms for Optical Burst-Switched Networks," in *Proc. 2003 IEEE International Workshop on Optical Burst/Packet Switching (WOBS 2003)*, Oct. 2003.
- [VOK03b] V. M. Vokkarane and J. P. Jue, "Prioritized Burst Segmentation and Composite Burst-Assembly Techniques for QoS Support in Optical Burst-Switched Networks," *IEEE Journal of Selected Areas in Communications*, Vol. 21, No. 7, pp. 1198 – 1209, Sept. 2003.

## *Bibliography*

---

- [VOK03c] V. M. Vokkarane, G. P. V. Thodime, V. U. B. Challagulla and J. P. Jue, "Channel Scheduling Algorithms Using Burst Segmentation and FDLs for Optical Burst-Switched Networks," in *Proc. IEEE ICC 2003*, Symposium on Optical Networking, Vol. 2, pp. 1443-1447, May 2003.
- [VOK05] V. M. Vokkarane and J. P. Jue, "Segmentation-Based Nonpreemptive Channel Scheduling Algorithms for Optical Burst-Switched Networks," *IEEE Journal of Lightwave Technology*, Vol.23, No. 10, pp. 3125-3137, Oct. 2005.
- [VU05] H. L. Vu, A. Zalesky, M. Zukerman, Z. Rosberg, J. Guo and T. W. Um, "Delay Analysis of Optical Burst Switching Networks," in *Proc. 2005 IEEE ICC 2005*, Symposium on Optical Networking, Vol. 3, pp. 1656-1662, May 2005.
- [WAN00] X. Wang, H. Morikawa and T. Aoyama, "Deflection Routing Protocol for Burst Switching WDM Mesh Networks," in *Proc. SPIE/IEEE Terabit Optical Networking: Architecture, Control, and Management Issues*, pp. 242-252, Boston, USA, Nov. 2000.
- [WAN02] X. Wang, H. Morikawa and T. Aoyama, "Burst Optical Deflection Routing Protocol for Wavelength Routing WDM Networks," *SPIE Optical Networks Magazine*, Vol. 3, No. 6, pp. 12-19, November/December 2002.
- [WAN02a] X. Wang, H. Morikawa and T. Aoyama, "Detection Routing-compatible Wavelength Assignment for Contention Resolution in Burst-switched Photonic Networks" in *Proc. Asia-Pacific Optical and Wireless Communications*

## *Bibliography*

---

- (*APOC2002*), 4910-4924, Shanghai, China, Oct. 2002.
- [WAN02b] X. Wang, H. Morikawa and T. Aoyama, "Priority-based Wavelength Assignment Algorithm for Burst Switched Photonic Networks," in *Proc. 2002 IEEE Optical Fiber Communications Conference (OFC 2002)*, pp. 765-767, Mar. 2002.
- [WAN03a] X. Wang, H. Morikawa and T. Aoyama, "Priority-based Wavelength Assignment Algorithm for Burst Switched WDM Optical Networks," *IEICE Transactions on Communications*, E86-B(5): 1508-1514, May 2003.
- [WAN03b] J. Wang, Q. Zeng, S. Xiao and Z. Zhang, "Segment Technology of Differentiated Services Supporting in Optical Burst Switched Networks," in *2003 IEEE International Workshop on Optical Burst/Packet Switching (WOBS 2003)*, 2003
- [WEI00] J.Y. Wei and R.I. McFarland, "Just-In-Time Signaling for WDM Optical Burst Switching Networks," *IEEE Journal of Lightwave Technology*, Vol. 18, No. 12, pp. 2019-2037, Dec 2000.
- [WID95] I. Widjaja, "Performance Analysis of Burst Admission-Control Protocols," *IEE Proceedings Communications*, Vol. 142, pp. 1206-1210, Feb. 1995.
- [XIO01] Y. Xiong, M. Vandenhoute and H. Cankaya, "Control Architecture in Optical Burst-switched WDM Networks," *IEEE Journal on Selected Areas in Communications*, Vol. 18, pp. 1838-1851, Oct. 2000.
- [XU01] L. Xu, H.G. Perros and G. Rouskas. "Techniques for Optical Packet Switching and

*Bibliography*

---

- Optical Burst Switching,” *IEEE Communications Magazine*, Vol. 39, No. 1, pp. 136-142, Jan. 2001.
- [XU03] J. Xu, C. Qiao, J. Li and G. Xu, “Efficient Channel Scheduling Algorithms in Optical Burst Switched Networks,” in *Proc. IEEE INFOCOM 2003*, Vol. 3, pp. 2268-2278, March-April 2003.
- [XU04] J. Xu, C. Qiao, J. Li and G. Xu, “Efficient Burst Scheduling Algorithm in Optical Burst-switched Networks Using Geometric Techniques,” *IEEE Journal on Selected Areas in Communications*, Vol. 22, No. 9, pp. 1769-1811, Nov. 2004.
- [XUE05] F. Xue, S.B. Yoo, H. Yokoyama and Y. Horiuchi, “Performance Comparison of Optical Burst and Circuit Switched Networks,” in *Proc. 2005 IEEE Optical Fiber Communications Conference (OFC 2005)*, Mar. 2005.
- [YAN03] L. Yang, Y. Jiang and S. Jiang, “A Probabilistic Preemptive Scheme for Providing Service Differentiation in OBS Networks,” in *Proc. IEEE Globecom 2003*, Symposium on Optical Networking, pp. 2689-2673, Dec. 2003.
- [YAO00a] S. Yao, B. Mukherjee and S. Dixit, “Advances in Photonic Packet Switching: An Overview,” *IEEE Communications Magazine*, pp. 84-94, Feb. 2000.
- [YAO00b] S. Yao, S. J. B. Yoo, B. Mukherjee and S. Dixit, “All-optical Packet-switched Networks: a Study of Contention-resolution Schemes in an Irregular Mesh Network with Variable-sized Packets,” in *Proc. SPIE OPTICOMM 2000*, Vol. 4233, pp.

### *Bibliography*

---

235-246, Plano, TX. Oct., 2000.

[YAO03] S. Yao, B. Mukherjee, S. J. B. Yoo and S. Dixit, "A Unified Study of Contention-resolution Schemes in Optical Packet-switched Networks," *IEEE Journal of Lightwave Technology*, Vol. 21, No. 3, pp. 672-683, Mar. 2003.

[YOO00a] M. Yoo, C. Qiao and S. Dixit, "A Comparative Study of Contention Resolution Policies in Optical Burst Switched WDM Networks," in *Proc. Conference on Terabit Optical Networking: Architecture, Control and Management Issues*, Vol. 4213, pp. 124-135, 2000.

[YOO00b] M. Yoo, C. Qiao and S. Dixit, "The Effect of Limited Fiber Delay Lines on QoS Performance of Optical Burst Switched (OBS) WDM Networks," in *Proc. 2000 IEEE International Conference on Communications (ICC 2000)*, Symposium on Optical Networking, pp. 974-979, June, 2000.

[YOO00c] M. Yoo, C. Qiao and S. Dixit, "QoS performance of Optical Burst Switching in IP-Over-WDM networks," *IEEE Journal on Selected Areas in Communications*, Vol. 18, pp. 2062-2071, Oct. 2000.

[YOO01] M. Yoo, C. Qiao and S. Dixit, "Optical Burst Switching for Service Differentiation in the Next-generation Optical Internet," *IEEE Communications Magazine*, Vol. 39, pp. 98-104, Feb. 2001.

[YOO97] M. Yoo and C. Qiao, "Just-Enough-Time (JET): A High Speed Protocol for Bursty

*Bibliography*

---

- Traffic in Optical Networks,” in *proc. IEEE/LEOS Conf. on Technologies For a Global Information Infrastructure*, pp. 26-27, Aug. 1997.
- [YOO98] M. Yoo and C. Qiao, “A New Optical Burst Switching Protocol for Supporting Quality of Service,” in *SPIE Proc. Conf. All-optical Networking*, Vol. 3531, pp. 396-405, 1998.
- [YOO99a] M. Yoo and C. Qiao, “A Novel Switching Paradigm for Bufferless WDM Networks,” in *Proc. 1999 IEEE Optical Fiber Communications Conference (OFC 1999)*, pp. 177-179, Mar. 1999.
- [YOO99b] M. Yoo and C. Qiao. “Supporting Multiple Classes of Services in IP Over WDM Networks,” in *Proc. IEEE GLOBECOM 1999, Symposium on Optical Networks*, pp. 1023-1027, Dec. 1999.
- [YU05a] O. Yu and H. Xu, “Adaptive Reliable Optical Burst Switching,” in *Proc. IEEE 2nd International Conference on Broadband Networks*, Vol. 2, pp. 1419 – 1427, Oct. 2005.
- [YU05b] O. Yu and M. Liao, “Synchronous Stream Optical Burst Switching,” in *Proc. IEEE 2nd International Conference on Broadband Networks*, Vol. 2, pp. 1447 – 1452, Oct. 2005.
- [YUA02] M. C. Yuang, J. Shih and P. L. Tien, “QoS Burstification for Burst Switched WDM Networks,” in *Proc. 2002 IEEE Optical Fiber Communications Conference*

*Bibliography*

---

(*OFC 2002*), pp. 781-783, Mar. 2002.

[ZAL04a] A. Zalesky, H. L. Vu, Z. Rosberg, E. W. M. Wong and M. Zukerman, "Modelling and Performance Evaluation of Optical Burst Switched Networks with Deflection Routing and Wavelength Reservation," in *Proc. IEEE INFOCOM 2004*, Vol. 23, No. 1, Hong Kong, China, pp. 1865–1872, Mar. 2004.

[ZAL04b] A. Zalesky, H. L. Vu, M. Zukerman, Z. Rosberg and E.W.M. Wong, "Evaluation of Limited Wavelength Conversion and Deflection Routing as Methods to Reduce Blocking Probability in Optical Burst Switched Networks," in *Proc. IEEE ICC 2004*, Symposium on Optical Networking, Vol.3, pp. 1543-1547, June 2004.

[ZAN00] H. Zang, J. Jue and B. Mukherjee, "A Review of Routing and Wavelength Assignment Approaches for Wavelength-routed Optical WDM Networks," *Kluwer Optical Networks Magazine*, Vol. 1, No. 1, pp. 47-60, Jan. 2000.

[ZHA03a] Q. Zhang, V. M. Vokkarane, B. Chen and J. P. Jue, "Early Drop Scheme for Providing Absolute QoS Differentiation in Optical Burst-switched Networks," in *Proc. 2003 IEEE Workshop on High Performance Switching and Routing (HPSR 2003)*, pp. 153 -157, June 2003.

[ZHA03b] Q. Zhang, V. M. Vokkarane, B. Chen and J. P. Jue, "Early Drop and Wavelength Grouping Schemes for Providing Absolute QoS Differentiation in Optical Burst-switched Networks," in *Proc. IEEE GLOBECOM 2003*, Symposium on Optical Networking, Vol. 5, pp. 2694-2698, Dec. 2003.

## *Bibliography*

---

- [ZHA04a] Q. Zhang, V. M. Vokkarane, B. Chen and J. P. Jue, "Path Clustering: an Approach to Implement Absolute QoS Differentiation in Optical Burst-switched Networks," in *Proc. IEEE GLOBECOM 2004*, Symposium on Optical Networking, Vol. 3, pp. 1999-2003, Nov.-Dec. 2004.
- [ZHA04b] Q. Zhang, V. M. Vokkarane, J. P. Jue and B. Chen, "Absolute QoS Differentiation in Optical Burst-switched Networks," *IEEE Journal of Selected Areas in Communications*, Vol. 22, No. 9, pp. 1781-1795, Nov. 2004.
- [ZHA06] Z. Zhang, L. Liu and Y. Yang, "Slotted Optical Burst Switching (SOBS) Networks," in *Proc. 2006 IEEE International Symposium on Network Computing and Applications*, pp. 111-117, July 2006.
- [ZHA95] H. Zhang, "Service Disciplines for Guaranteed Performance Service in Packet Switching Networks," *IEEE Proceedings*, Vol. 83, pp. 1374-1396, Oct. 1995.
- [ZIV02] A. Ziviani, J. F. de Rezende and O. C. M. B. Duarte, "Evaluating the Expedited Forwarding of Voice Traffic in a Differentiated Services Network," *Wiley International Journal of Communication Systems*, Vol. 15, No. 9, pp. 799-813, Nov. 2002.

## Publications

1. Hongbo Lui and Hussein T. Mouftah, "Providing Absolute Quality-of-Service Differentiation in Optical Burst Switching Networks", *IEEE Journal of Optical Networks*, submitted.
2. Hongbo Lui and Hussein T. Mouftah, "Per-Hop Absolute Quality-of-Service Differentiation in OBS Networks", *IEEE Journal of Lightwave Technology*, submitted.
3. Hongbo Lui and Hussein T. Mouftah, "Extended Reserve-and-Preempt Scheme for Providing Absolute QoS Differentiation IN OBS Networks," Fourth Workshop on Optimization of Optical Networks (OON07), May 2007, Montreal, Canada
4. Hongbo Lui and Hussein T. Mouftah, "A New Absolute QoS Differentiation Scheme Supporting Best-Effort Class in OBS networks," IEEE 9<sup>th</sup> International Conference on Transparent Optical Networks July 1-5, 2007, Rome, Italy
5. Hongbo Lui and Hussein T. Mouftah, "Absolute QoS Differentiation with Best-Effort Class Support in Optical Burst Switching Networks", IEEE Symposium on Computers and Communications, July1-4, 2007, Averio, Portugal

*Bibliography*

---

6. Hongbo Lui and Hussein T. Mouftah, "Segmentation-based random dropping scheme in OBS networks", Third Workshop on Optimization of Optical Networks (OON06), April 2006, Montreal, Canada
7. Hongbo Lui and Hussein T. Mouftah, "A Segmentation-Based Dropping Scheme in OBS Networks," IEEE 8th International Conference on Transparent Optical Networks, June 18-22, 2006 - Nottingham, United Kingdom