

# **Providing Absolute QoS in OBS Networks through Virtual Channel Reservation**

Presented By

**GUAN XIN**

Submitted in total fulfilment of the requirements of the degree of

**Master of Engineering**

Department of Electronic and Computer Engineering

National University of Singapore

3 August, 2004

# Acknowledgments

I am deeply indebted to my supervisor Dr. Ian Li-Jin Thng and Dr. Jiang Yuming, who provide constant encouragement and help in my work. I am very fortunate to have been able to work with them, their dedication to research, precise attitude towards nuances and subtleties in science and expert guidance in research ways benefit me a lot. Their wise comments, conversations and insights have found their way into my thoughts and onto these pages.

My deepest gratitude, love and admiration belong to my parents and all my family members, whose selfless encouragements and supports are always inspiring my efforts and achievements.

I would also like to give my sincere appreciations to my boy friend, Mr. Guo Jianyu, who always supports and encourages me, and gives his valuable comments.

# Contents

<b>Acknowledgments .....</b>	<b>i</b>
<b>Summary.....</b>	<b>iv</b>
<b>List of Figures.....</b>	<b>vi</b>
<b>List of Tables .....</b>	<b>vii</b>
<b>Chapter 1 Introduction .....</b>	<b>1</b>
1.1 Optical Burst Switching Networks .....	1
1.2 Quality of Service in IP-over-WDM Networks.....	3
1.3 Current Proposed QoS Schemes in OBS Networks .....	5
1.4 The Proposed Scheme.....	8
1.5 The Structure of this Thesis .....	8
<b>Chapter 2 Virtual Channel Reservation Scheme .....</b>	<b>10</b>
<b>Chapter 3 Theoretical Analysis.....</b>	<b>13</b>
3.1 The dropping probability Analysis .....	14
3.2 Threshold calculation Algorithm.....	18
3.3 The conformance of VCR to Conservation Law .....	20
<b>Chapter 4 VCR Performance for the Single Node Scenario .....</b>	<b>24</b>
4.1 Conformance of VCR to Conservation Law.....	24
4.2 Comparison of the Two-Class System with JET QoS and GC schemes.....	28
4.2.1 Comparison with JET QoS .....	28
4.2.2 Comparison with GC .....	30
4.3 Performance evaluation of the three-class system.....	32
<b>Chapter 5 I-header and VCR Performance for the Multi-node Scenario .....</b>	<b>34</b>

5.1	Weakness of VCR in multi-node networks .....	35
5.2	The i-header mechanism.....	36
5.3	Performance improvements in a multi-node scenario with i-header .....	39
5.4	Performance comparison of VCR, VCR-I with other QoS schemes in a multi- node Scenario .....	43
5.4.1	Two-class system.....	44
5.4.1.1	Comparison with the JET QoS scheme.....	44
5.4.1.2	Comparison with the GC scheme.....	48
5.4.2	Three-class system.....	49
<b>Chapter 6</b>	<b>Conclusion.....</b>	<b>51</b>
<b>Bibliography</b> .....	<b>53</b>	
<b>Appendix A</b> .....	<b>55</b>	

# Summary

Optical Burst Switching (OBS) networks provide good features to support IP-over-photonics for the next generation Internet. As OBS networks are built with huge bandwidth capacity and very high speed transmission technology, it is critical and challenging to satisfy their requirements on quality of service. This thesis proposes a new absolute QoS differentiation scheme call Virtual Channel Reservation (VCR) scheme for Optical Burst Switching (OBS) networks. The scheme provides worst case guarantee on the dropping probability of higher priority classes. In existing literature, there are very few contributions that support efficient absolute QoS guarantee in OBS networks, which is critical for burst drop sensitive applications. The service differentiation among each priority class in VCR is achieved by applying the concepts of virtual channel reservation and preemption, rather than by implementing optical buffer or extra offset time. Preemption in OBS literature often means that discard of a scheduled burst or a burst in service. One potential side effect of preemption, however, is bandwidth underutilization in multi-node scenarios. To address this problem, we also contribute a new *informing header (i-header)* mechanism. Simulations are conducted to evaluate the performance of VCR, both with and without i-headers. Results show that VCR without i-headers is able to meet the absolute QoS requirements in both single-node and multi-node scenarios. In addition, the introduction of i-header effectively reduces downstream bandwidth wastage caused by preemption in the multi-node scenario. The contribution of VCR and i-header is

significant for the following practical reasons. Firstly, VCR does not use optical buffers or extra offset time to achieve service differentiation; hence the problem of path length priority effect or long end-to-end delay problems will not arise. Secondly, VCR conforms theoretically to the Conservation Law; hence as far as overall dropping probability is concerned, VCR will outperform other QoS techniques like Guard Channel (GC) and JET QoS schemes. The last statement will be verified both theoretically and by the many simulation scenarios presented in the thesis.

## List of Figures

Figure 2.1 The working algorithm of VCR .....	11
Figure 3.1 Threshold calculation algorithm.....	20
Figure 4.1 Computational and simulation comparisons .....	25
Figure 4.2 Drop probability vs. Class 1 QoS requirement for two-class system.....	26
Figure 4.3 Drop probability vs. Class 1 QoS requirement for three-class system.....	27
Figure 4.4 Overall drop probability of VCR vs. Threshold.....	28
Figure 4.5 Comparison of VCR with JET QoS in a single node scenario.....	30
Figure 4.6 VCR vs. GC in a single node scenario .....	31
Figure 4.7 VCR drop probability vs. load in the three-class system .....	32
Figure 5.1 An OBS network model .....	35
Figure 5.2 Performance improvement of VCR-I vs. VCR .....	42
Figure 5.3 VCR and VCR-I vs. JET QoS in a multi-node scenario .....	46
Figure 5.4 VCR and VCR-I vs. GC in a multi-node scenario .....	49
Figure 5.5 VCR Drop probability for absolute QoS in a three-class system.....	50

# List of Tables

Table 1. Computational drop probability, with total 2 channels .....	22
Table 2. Thresholds in two-class system for absolute QoS, $P_{1\_QoS} = 1e-04$ .....	31
Table 3 VCR thresholds for a three-class system to achieve absolute QoS requirements; $P_{1\_QoS} = 1e-04$ ; $P_{2\_QoS} = 1e-03$ .....	32
Table 4 QoS requirement and Threshold settings for VCR and VCR-I in two-class system.....	45



# Chapter 1

## Introduction

As the popularity of Internet grows, due to emerging multimedia applications such as video conference, HDTV, Internet telephony, and digital audio, the demand for a higher transmission capacity is also rising drastically. Optical Internet by using wavelength division multiplexing (WDM), now becomes attractive as a promising approach building next generation Internet. Compared with the ATM and SONET layers, it is less complexities and overheads. Having the huge deliverable bandwidth, Optical Internet could bypass the potential bottleneck in electronic routers. It will provide direct high speed/high bandwidth communication channels, so that high communication efficiency can be achieved.

### 1.1 Optical Burst Switching Networks

The current existing optical switching techniques include optical circuit switching, optical packet switching, and optical burst switching. Optical circuit switching networks provide circuit-switched lightpath services where lightpaths need to be established first from the source node to the destination node using a dedicated wavelength on each link along a physical path. Such networks require a two-way reservation protocol to set up the circuit and may underutilize the bandwidth. In optical packet switching networks, a fixed size packet is sent along with its header and the

packet is optically buffered or delayed at the intermediate node while the header is processed electronically. Due to the limitation of current technologies on packet synchronization as well as optical buffer design, optical packet switching network is not yet mature.

As an alternative, optical burst switching (OBS) leads to a better solution for IP over WDM [1, 2]. It combines the advantages of both Wavelength-Routed (WR) networks and Optical Packet Switching (OPS) networks. As in WR networks, there is no need for buffering and electronic processing for data at the intermediate nodes. At the same time, OBS increases the network utilization by reserving the channel for a limited time period. In OBS networks, one or more IP packets, which are destined for the same address and meet certain pre-defined criteria, may be assembled into a data burst. A control header is then generated for each data burst and transmitted slightly ahead of the data burst on a separate channel. Making use of the one-way reservation protocol, OBS leaves a small time gap between the control header and the data burst so that data transmission starts without waiting for the acknowledgement to come back. The time gap is chosen to be greater than or equal to the total processing delay encountered by the control header.

Several signalling protocols have been proposed for OBS [3]. Qiao and Yoo have proposed a protocol called Just-Enough-Time (JET) [2]. JET is a reserve-a-fixed duration (RFD) scheme that reserves resources exactly for the transmission time of the burst. This signalling protocol only requires the control headers contain the information about the destination address, the data burst length, the wavelength on which the associated data burst will arrive and the offset time. On top of that, a few

channel-scheduling algorithms have been proposed in literatures [4], [5], and [1]. From these algorithms, the Latest Available Unused Channel with Void Filling (LAUC-VF) algorithm yield the best performance in terms of burst dropping probability. The basic idea of the LAUC-VF algorithm is to minimize voids by selecting the latest available unused channel for each arriving burst.

## **1.2 Quality of Service in IP-over-WDM Networks**

Over the past decade, a significant amount of work has been dedicated to the issue of providing Quality of Service (QoS) in non-WDM IP networks. Basic IP assumes a best effort service model. In this model, the networks allocate bandwidth to all active users as best as it can, but does not make any explicit commitment as to bandwidth, delay, or actual delivery. This service model is not adequate for many real-time applications that normally require assurances on the maximum delay of transmitting a packet through the network connecting the end points. Thus there is a demand for replacing existing best-effort service with a model in which packets, applications and users are treated differently based on their required quality of service.

QoS refers to the nature of the packet delivery service provided by a network. According to International Telecommunication Union (ITU) Recommendation E.800, quality of service is “the collective effect of service performances which determine the degree of satisfaction of a user of the service”. The primary goals of QoS include dedicated rate or throughput, improved loss characteristics and controlled delay. While quality of service can have many other aspects such as security, reliability and availability of a connection, throughput, loss and delay are the three critical aspects for most applications.

A number of enhancements have been proposed to enable offering different level of QoS in IP networks. This work has culminated in the proposal of the Integrated Services (Intserv) [6] and the Differentiated Services (Diffserv) [7] architectures by the IETF. Intserv achieves QoS guarantees through end-to-end resource reservation for packet flows and performing per-flow scheduling in all intermediate routers or switches. Diffserv, on the other hand, defines a number of per-hop behaviors that enable providing relative QoS advantage for different classes of traffic aggregates. Both schemes require sources to shape their traffic as a precondition for providing end-to-end QoS guarantees. Since Internet traffic will eventually be aggregated and carried over the core networks, it is imperative to address end-to-end QoS issues in WDM networks.

However, the QoS problem in optical WDM networks has several fundamental differences from QoS methods in electronic routers and switches. One major difference is the absence of the concept of “packet queues” in WDM devices, beyond the Fibre Delay Lines (FDLs). FDLs are long fibre lines used to delay the optical signal for a particular period of time. As an alternative to queuing, optical networks use additional signalling to reserve bandwidth on a path ahead of the arrival of optically switched data.

QoS support is an important issue in OBS networks. Applications with diverse QoS requirements urge the Internet to guarantee QoS. To provide service differentiation, the traffic is classified into classes. QoS of each class is defined relatively to other classes or quantitatively in absolute terms based on loss, delay or

bandwidth. The later type of hard guarantee is essential for the classes of delay and loss sensitive applications.

### 1.3 Current Proposed QoS Schemes in OBS Networks

To cater for the different requirements for burst drop by different traffic classes in OBS networks, many algorithms have been proposed. These algorithms can be classified into two categories: relative QoS differentiation schemes and absolute QoS differentiation schemes. In the former category, the performance of each traffic class is defined relatively to other classes; while in the latter category, the QoS requirement for each class is defined quantitatively in absolute terms. The absolute QoS performance guarantee is essential for drop-sensitive applications. Efficient resource provisioning and good admission control are crucial to support the absolute QoS differentiation.

Some of the relative QoS schemes rely on buffers. In current optical networks, however, no efficient optical buffers are available. Hence such buffer-based schemes are not preferable. The JET QoS scheme [2] takes advantage of extra offset time to separate different traffic classes. Assume two classes of service are provided: Class 1 and Class 0. Class 1 is the real-time service class that corresponds to applications that require low delay, bandwidth guarantee and low dropping probability, while class 0 is the best effort service class. In order for class 1 to have higher priority for bandwidth reservation, an additional offset time ( $t_{qos}$ ) is given to this class. The value of  $t_{qos}$  is constant and considerably larger than the original JET offset time. Additionally,  $t_{qos}$  needs to be larger than the maximum burst length in class 0. With such long offset time, the dropping probability of bursts in Class 0 becomes independent of the offered load in Class 1. The author in [2] also gave a simple analytical model to evaluate the

dropping probability as a function of  $t_{qos}$ , and concluded that to provide 100% isolation between Class 0 and Class 1, it is sufficient to have  $t_{qos}$  equals to five times the average burst length of Class 0. However, recent studies have pointed out a number of drawbacks of this scheme. One is the “path length priority effect” [8]; another is the “unfavorable end-to-end delay” [9]. The former results from the fact that, in JET QoS, a larger offset time inflicts a lower burst blocking probability. Therefore, a burst with more remaining hops will enjoy a lower blocking probability than that with fewer remaining hops. For the latter, although a longer offset time between header and burst may ensure a lower blocking probability, it also introduces a longer delay for the burst. Other than the two schemes, a segmentation-based scheme is proposed in [10], which assembles segments of different priority into a burst at network ingress nodes. Packets are placed in each burst in the order of decreasing priority. Whenever contention occurs, lower priority packets, which tail the burst, will be deflected. The extra costs of this scheme are the burst assembly complexity at the ingress nodes and the burst scheduling complexity at intermediate nodes. Another scheme proposed in [9] is called intentional dropping scheme, which maintains the drop rate of each traffic class at a predefined proportion. A burst is dropped if the predefined drop rate of its class is violated, regardless of whether there is an idle channel. This scheme guarantees that the traffic from a higher priority class will receive better service; however it can cause excessive dropping and result in low bandwidth utilization.

While absolute QoS support in OBS network is desirable for drop sensitive bursts, there are but only a few absolute QoS schemes contributed in the literature. Often times, absolute QoS schemes are heuristic, based on control feedback mechanisms and are normally limited to two classes only. Due to the possibility that feedback signals

can be late or unstable, heuristic based QoS approaches introduce fuzzy parameters which must be tweaked to ensure some level of safety margin between the simulated drop probability and the desired QoS. In other words, these schemes are highly inconvenient to use in that should the QoS requirement change, hours of simulations must be conducted again to tweak the fuzzy parameters to suit the new absolute QoS requirement. Absolute QoS dimensioning beyond two classes in a heuristic based scheme is also difficult to achieve since the mechanism is heuristic. Absolute QoS dimensioning is defined as allocating an appropriate absolute burst drop probability for a class. For example, consider allocation of absolute burst drop probability for three classes. The top priority class is allocated a drop probability of, say,  $10^{-4}$ , the middle priority class is allocated a burst drop probability of  $10^{-3}$  and the lowest priority class is not given any burst drop probability requirement. Under a heuristic mechanism, one is never sure whether any of these absolute burst drop probabilities can be achieved and even if they are achieved, it is normally at the expense of over-dropping the lowest priority class. In other words, it is very difficult to demonstrate that heuristic based schemes conform to the Conservation Law on burst drop probabilities. The Conservation Law on burst drop probability states that the overall drop probability of a node which prioritizes bursts is the same as the overall drop probability of a node that does not prioritize bursts (i.e. classless scenario). This property is important in that when priority is introduced on the system, the system does not over punish the lowest priority class in order to satisfy the priority requirements. Hence, as far as throughput is concerned, a node providing priority QoS which conforms to the Conservation Law has the same throughput as a node that does not provide priority QoS. In other words, there is no trade-off in throughput when priority QoS is implemented.

## 1.4 The Proposed Scheme

In view of the drawbacks of the above-mentioned schemes, we propose in this thesis a new scheme, **Virtual Channel Reservation (VCR)** scheme, for providing absolute QoS in OBS networks. This is a pure theoretical, non-heuristic, non-feedback scheme, which we derive not only for two-class absolute QoS but also for three-class absolute QoS. Technically, VCR can be extended to more classes as well. However, it is rare to find networks providing QoS classes that exceed three classes. For example, the popular DiffServ standard defines up to three QoS classes. The VCR idea came from the observation that channel reservation is a commonly used method for achieving service differentiation in electronic networks, where extensive research has been conducted. Among various schemes that make use of channel reservations, the Guard Channel (GC) scheme [10] is the most famous one. In a system with two traffic classes, the GC scheme will reject an incoming low priority header request, whenever the number of occupied channels reaches the predefined threshold. In contrast, a high priority burst will be dropped only if all channels are occupied at the time its header arrives. GC is computationally inexpensive to implement and can be used as a benchmark system to gauge the VCR technique. In the thesis, we shall compare its performance with the proposed VCR scheme. It is important to note that the VCR scheme conforms to the Conservation Law, unlike the GC scheme and other heuristic based schemes.

## 1.5 The Structure of this Thesis

In this Introduction, the challenges that motivate the study in this thesis have been addressed. The remainder of this thesis is organized as follows.



In Chapter 2, a new QoS scheme for OBS networks, named Virtual Channel Reservation Scheme is proposed. It is able to provide multi-class service differentiation without making use of buffer or extra offset time. The working algorithm of this scheme has been described.

In Chapter 3, the VCR scheme is analyzed in detail on its dropping probability for two-class, three-class and multi-class system through multi-dimensional Markov Chain. An algorithm is then contributed to enable absolute QoS dimensioning in a two-class and three-class OBS network. In addition, VCR conformance to Conservation Law is also demonstrated.

In Chapter 4, the VCR performance in both two-class and three-class single-node scenario is studied. VCR is compared with JET QoS Scheme and Guard Channel Scheme.

Chapter 5 presents the problems that VCR encounters in multi-node scenario, proposes the i-header mechanism to improve its drop probabilities. This chapter also evaluates the performance of VCR for a given QoS requirement in multi-node cases and compares VCR with the JET QoS scheme.

Finally, Chapter 6 summarize the work presented in this thesis, conclusion and remarks are made.

## Chapter 2

# Virtual Channel Reservation Scheme

The VCR scheme makes use of two concepts: virtual channel reservation and preemption. Suppose that a switch node has a total of  $T$  channels per output link. The traffic is classified into  $N$  different classes, which are denoted as  $c_1, c_2, \dots, c_N$ . The service priorities of class  $c_1, c_2, \dots, c_N$  are assumed to be in an descending order such that  $c_1$  represents the class with the highest priority and  $c_N$  the lowest. The higher the priority, the lower the burst dropping probability should be. The switch assigns each class a threshold value  $k_i$  ( $0 \leq k_i \leq T$ ), which is used to limit the occupation of channels by traffic of class  $i$ . However, this threshold is dormant and never applied when plenty of channels are available. This threshold value is only applied when channels are all occupied. Specifically, whenever a suitable available channel is found, reservation request for the desired period made by any incoming control header, regardless of its priority class, will always be granted; if all channels happen to be reserved upon the arrival of a class  $i$  control header, preemption will occur in a lower priority class  $j$ , where  $j \in i+1, \dots, N$ . This is done by first counting the number of channels already occupied by the bursts of its own priority class. If and only if the number turns out to be smaller than its predefined threshold  $k_i$ , will the preemption action on a lower priority class be triggered; otherwise, the incoming class  $i$  control header will be dropped. Obviously, a larger threshold leads to a lower dropping probability of the

particular class. The selection of the burst to preempt always starts from the lowest priority class. A burst of the second lowest priority class will be considered only when no burst of the lowest priority class can be found, and so on. If no burst of lower priority classes can be found at that time, the incoming control header will have to be dropped. This preemption policy is illustrated algorithmically in Figure 2.1. Furthermore, when preemption is to take place within a particular priority class, the burst with the latest starting time will be selected and preempted. The reason for this can only be explained in Chapter 5 when the i-header mechanism is introduced.

```

If (NumberofReservedChannel < T)
    Reserve it;
else
    if (i == N)
        Drop it;
    else
        for (j = N; j > i; j--)
            if (NumberofReservedChannelbyClass_j > 0)
                preempt class j burst;
                break from for loop;
        if (No preemption)
            drop class i header;
    
```

Figure 2.1 The working algorithm of VCR

From the above description, VCR has the following key features:

- (1) VCR does not require buffers. All decisions whether to drop the burst or preempt a lower priority burst, is made on the arrival of the control header of the burst.
- (2) Preemption in VCR is equivalent to the cancellation of a reserved transmission period. This can occur before transmission occurs or even during the transmission.
- (3) Various absolute QoS dropping probabilities can be achieved by assigning different thresholds,  $k_i$ , for each priority class.

(4) Unlike the GC scheme, where channels are permanently reserved for high priority classes, VCR does not permanently reserve channels. In fact, all channels are available to any class at any time. Only when the system is full will VCR start using the threshold to be sure that a particular class gets the amount of channels that the class has been allocated. This “virtual” method of channel reservation maximizes all the channel resources of the node ensuring no wastage of bandwidth resources. Consequently, the VCR technique conforms to the Conservation Law, this will be verified theoretically and through simulations later.

(5) The only drawback of the VCR scheme is that it requires preemption of bursts that have already been successfully scheduled. This may waste channel reservations already made for these preempted bursts in downstream nodes. Hence, as will be described later, another mechanism, which we name as i-header mechanism, is required to resolve this difficulty.

## Chapter 3

### Theoretical Analysis

In this chapter, we analyse the drop probabilities of VCR in several multi-class scenarios. An algorithm that is useful for QoS dimensioning is also contributed to provide absolute QoS differentiation in an N-class scenario. Thereafter, analytical studies, with verification from simulation studies are presented to demonstrate the conformation of VCR to the Conservation Law. Since networks catering to four classes and above are rare, we only consider detailed analysis up to three classes. However, we also explain in a chapter how the analysis can be extended beyond three classes. All analysis will be based on the following assumptions:

- The arrival process of class  $i$  bursts is Poisson with the rate  $\lambda_i$ . In [12], it is shown that Poisson arrival processes approximate real burst arrivals well.
- The service time of each class is exponentially distributed with the same mean service rate,  $\mu$ .
- There are T channels in total.
- Full wavelength conversion is assumed for VCR. This assumption is also used in many other QoS schemes contributed in OBS literature.

### 3.1 The dropping probability Analysis

The purpose of analyzing the drop probability of the VCR scheme is to establish the relationship between the VCR threshold and the drop probability of each priority class so that we can determine the value of the VCR threshold for a particular class, in order to meet the absolute QoS requirement. To this effect, we now present the following important Lemmas.

**Lemma 1:** In a two class VCR system, let  $P_1$  and  $k_1$  denote, respectively, the drop probability and the VCR threshold value for the high priority class 1 burst. Let  $P_2$  denote the drop probability of the lower priority class 2 burst. If there are  $T$  channels in this VCR node, then the following drop probabilities apply:

$$P_1 = \sum_{\{(n_1, n_2) \mid n_1 + n_2 = T; n_1 \geq k_1\}} p(n_1, n_2) \quad (1)$$

$$P_2 = \sum_{\{(n_1, n_2) \mid n_1 + n_2 = T\}} p(n_1, n_2) + \frac{\lambda_1}{\lambda_2} \sum_{\{(n_1, n_2) \mid n_1 + n_2 = T; 0 \leq n_1 < k_1\}} p(n_1, n_2) \quad (2)$$

where  $p(n_1, n_2)$  represents the state probability when the system has  $n_1$  number of class 1 burst reservations and  $n_2$  number of class 2 burst reservations.

**Proof:** The proof of (1) and (2) in Lemma 1 is based on analyzing the states of a two-dimensional Markov Chain state transition diagram. In particular, those states at the edge of the two-dimensional transition state diagram are of concern since those states represent the case where all  $T$  channels are fully utilized and hence the VCR threshold for class 1 will be activated. Since the analysis and proof are rather extensive and mathematical, the full proof is presented in Appendix A. W

**Remark:** Lemma 1 presents the required relationship for the design of the  $k_1$  VCR threshold for the higher priority class. The desired absolute QoS for class 1 is substituted into  $P_1$  and an algorithm that solves for  $k_1$  is then executed on the right hand side of (1). This algorithm will be presented later. It should be noted that if the absolute QoS is too stringent (i.e. too low), the derived value of  $k_1$  may exceed  $T$  (i.e., the maximum number of channels that the VCR mechanism can virtually reserve). If this happens, it means that the absolute QoS cannot be theoretically achieved by the VCR mechanism. Equation (2) represents the resulting drop probability for the lower priority class for a given higher priority VCR threshold value.

The following Lemma 2 is for a three class VCR system:

**Lemma 2:** In a three class VCR system, let  $P_1$ ,  $P_2$  and  $P_3$  denote the drop probabilities of the high, medium and low priority classes respectively. Let  $k_1$  and  $k_2$  denote the VCR thresholds for the high and medium priority classes, respectively. If there are  $T$  channels in this VCR node, then the following drop probabilities apply:

$$P_1 = \sum_{\{(n_1, n_2, n_3) \mid n_1 \geq k_1, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) \quad (3)$$

$$P_2 = \sum_{\{(n_1, n_2, n_3) \mid n_2 \geq k_2, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) + \sum_{\{(n_1, n_2, n_3) \mid n_2 < k_2, n_3 = 0, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) + \frac{\lambda_1}{\lambda_2} \sum_{\{(n_1, n_2, n_3) \mid n_1 < k_1, n_3 = 0, n_2 \neq 0, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) \quad (4)$$

$$\begin{aligned}
 P_3 = & \sum_{\{(n_1, n_2, n_3) \mid n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) + \\
 & \frac{\lambda_1}{\lambda_3} \sum_{\{(n_1, n_2, n_3) \mid n_1 < k_1, n_3 \neq 0, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) + \\
 & \frac{\lambda_2}{\lambda_3} \sum_{\{(n_1, n_2, n_3) \mid n_2 < k_2, n_3 \neq 0, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3)
 \end{aligned} \tag{5}$$

where  $p(n_1, n_2, n_3)$  represents the state probability when the system has  $n_1$  number of class 1 burst reservations,  $n_2$  number of class 2 burst reservations and  $n_3$  number of class 3 burst reservations.

**Proof:** The proof of (3), (4) and (5) in Lemma 2 is based on analyzing the states of a three-dimensional Markov Chain state transition diagram. In particular, those states at the side of the three-dimensional transition state diagram are of importance since those states represent the case where all  $T$  channels are fully utilized and hence the VCR threshold for class 1 or class 2 will be activated. Since the analysis and proof are rather extensive and mathematical, the full proof is presented in Appendix B. W

**Remarks:** The main purpose of working out the three-class VCR system in Lemma 2 is to obtain a pattern in the drop probabilities of the VCR system as more classes are considered. This aids in the deduction of a theorem for the general  $N$ -class VCR system to be presented later. In the three class system, the  $k_1$  VCR threshold for the highest priority class is first solved for a given absolute QoS value  $P_1$  using Equation (3). This  $k_1$  VCR threshold value is then used in (4) to solve for the  $k_2$  threshold for the next given absolute QoS value  $P_2$ . After obtaining both  $k_1$  and  $k_2$  VCR thresholds, the resulting drop probabilities for the last priority class  $P_3$  can be finally calculated using Equation (5). Similar to the two class system, if the calculated VCR thresholds,



i.e.  $k_1$  and  $k_2$ , exceed  $T$  (the total number of channels in the VCR node), this means that the absolute QoS requirement for the higher priority classes are too stringent.

The following Theorem 1 is for the general  $N$ - class VCR system:

**Theorem 1:** Let  $P_i$  and  $k_i$  denote the drop probability and the VCR threshold value for class  $i$  bursts respectively. The drop probabilities,  $P_1, P_2, \dots, P_N$ , for the  $N$  traffic classes in an  $N$ -class VCR system operating in an OBS node with  $T$  channels can be expressed as follows:

$$P_1 = \sum_{\{(n_1, \dots, n_i, \dots, n_N) \mid n_1 \geq k_1, n_1 + \dots + n_i + \dots + n_N = T\}} p(n_1, \dots, n_i, \dots, n_N) \quad (6)$$

$$\begin{aligned} P_i = & \sum_{\{(n_1, \dots, n_i, \dots, n_N) \mid n_i \geq k_i, n_1 + \dots + n_i + \dots + n_N = T\}} p(n_1, \dots, n_i, \dots, n_N) \\ & + \sum_{\left\{ (n_1, \dots, n_i, \dots, n_N) \mid n_i < k_i, \prod_{j=i+1}^N n_j = 0, n_1 + \dots + n_i + \dots + n_N = T \right\}} p(n_1, \dots, n_i, \dots, n_N) \\ & + \sum_{l \in \{1, \dots, i-1\}} \sum_{\left\{ (n_1, \dots, n_i, \dots, n_N) \mid n_l < k_l, n_l \neq 0, \prod_{j=l+1}^N n_j = 0, n_1 + \dots + n_i + \dots + n_N = T \right\}} \frac{\lambda_l}{\lambda_i} p(n_1, \dots, n_i, \dots, n_N) \end{aligned} \quad (7)$$

$$\begin{aligned} P_N = & \sum_{\{(n_1, \dots, n_i, \dots, n_N) \mid n_1 + \dots + n_i + \dots + n_N = T\}} p(n_1, \dots, n_i, \dots, n_N) \\ & + \sum_{l \in \{1, \dots, N-1\}} \sum_{\{(n_1, \dots, n_i, \dots, n_N) \mid n_l < k_l, n_l \neq 0, n_1 + \dots + n_i + \dots + n_N = T\}} \frac{\lambda_l}{\lambda_i} p(n_1, \dots, n_i, \dots, n_N) \end{aligned} \quad (8)$$

where  $2 \leq i \leq N-1$ ,  $p(n_1, \dots, n_i, \dots, n_N)$  represents the state probability when the system has  $n_1$  number of class 1 burst reservations,  $n_2$  number of class 2 burst reservations and  $n_i$  number of class  $i$  burst reservations and so on.

**Proof:** The proof is obtained by observing a clear pattern in the drop probabilities of the two class VCR system and the three class VCR system presented in Lemmas 1 and 2. W

**Remark:** In the general  $N$ -class VCR system, it is noted that the drop probability of class  $i$ , i.e.  $P_i$ , depends on the VCR threshold values of class 1 to class  $i$ , i.e.  $k_1, k_2, \dots, k_{i-1}$ . Therefore, given the QoS requirements for class 1 to class  $N-1$ , or drop probabilities  $P_1, \dots, P_{N-1}$ , the corresponding VCR thresholds  $k_1$  to  $k_{N-1}$  can be determined very much the same way the VCR thresholds for the two-class and three-class systems are obtained. If any of the VCR thresholds were to exceed  $T$  (the total number of channels in the VCR node), this means that the absolute QoS requirement for the associated higher priority class is too stringent.

The threshold calculation algorithm, for calculating the VCR thresholds,  $k_1$  to  $k_{N-1}$ , is now contributed in the next section.

### 3.2 Threshold calculation Algorithm

By virtue of the analysis of drop probabilities and balance equations in the two-class, three-class and the  $N$ -Class VCR systems, we are now ready to contribute an algorithm that is able to determine the thresholds of prioritized classes so as to meet a given QoS requirement. This algorithm is presented in Figure 3.1, where  $P_{i\_QoS}$  is

assumed to be the QoS drop probability requirement for class  $i$  and  $k_i$  represents the VCR threshold value of class  $i$ . The function *Solve\_Balance\_Equations* ( $k_1, k_2, \dots, k_{N-1}$ ) uses the associated state balance equations to compute the state probabilities by taking a set of threshold values as its parameters. For the two and three class system, the state balance equations are presented in Appendix A and B respectively. Another function in the algorithm, i.e. *Compute\_class\_i\_dropping\_probability()*, makes use of the drop probability expressions found in Lemma 1, Lemma 2 and Theorem 1 to compute the drop probability of class  $i$ . The threshold calculation algorithm can be easily programmed to work out a suitable VCR threshold that will guarantee a specified drop probability for a particular class of traffic.

```

/*****
/* Threshold Calculation Algorithm*/
/*****
main() /*Compute all thresholds for N number of classes*/
{
    Compute_all_classes_threshold(N, M);
}

Compute_all_classes_threshold(int n, int i)
{
    if (i>1) /*Compute all thresholds for class 1 to i-1*/
    {
        {Compute_all_classes_threshold(n, i-1);
        Compute_class_i_threshold(n, i); }
    }
    else
        Compute_class_i_threshold(i,1);
}

Compute_class_i_threshold (intn, int i)
{
    for (ki = 0; ki ≤ T; ki++)
    {
        /* Solve balance equations to get the probability of each state in the state diagram*/
        p(n1, n2, ... nN) = Solve_Balance_Equations(k1, k2, ... kN-1);
        /* Calculate the dropping probability of each class */
        Pi = Compute_class_i_dropping_probability();
        /* Compare with the QoS dropping probability */
        If (Pi < Pi_QoS)
        {
            Threshold i = ki;
            Break;
        }
    }
}
}

```

Figure 3.1 Threshold calculation algorithm

### 3.3 The conformance of VCR to Conservation Law

The *Conservation Law* [13] states that the sum of the burst drop probabilities encountered by a set of traffic classes, weighted by their share of arrival rates, is independent of the scheduling discipline. An absolute QoS scheme, which conforms to the Conservation Law, not only provides guaranteed QoS differentiation, but does so without over sacrificing the lower priority class performance. The overall drop probability of such a scheme is similar to the drop probability of a classless scheme and hence it is expected to have better drop probability performance compared to other

QoS schemes which do not conform to the Conservation Law. The purpose of this chapter is to demonstrate that the VCR system conforms to the Conservation Law. For this purpose, we present Theorem 2 as follows:

**Theorem 2:** The overall drop probability of the multi-class single-node VCR system conforms to the Conservation Law.

**Proof:**

(1) In a single-node VCR system, all the offset time are the same, whether high or low priority.

(2) All channels are always utilized before a preemption occurs.

(3) When preemption occurs, it is just a replacement of one burst with another burst that has the same offset time. Hence there is no change in the overall drop probability when preemption occurs.

(4) Based on the above three observations, since all, the VCR system is equivalent to a classless OBS system where all the bursts have the same offset time.

(5) Since the classless OBS system where all the bursts have the same offset time is conservative. Therefore, VCR system is also conservative.  $\square$

**Remark:** We can also demonstrate a theoretical analysis for the conformance of conservative for the two-class system, since it is simple enough to show the explicit expressions for the drop probabilities. In Table 1, we assume a two-channel system, i.e.  $T=2$ , then we calculate the overall drop probabilities  $P_{overall}$  of VCR thresholds 0,1 and 2, where  $P_1$  and  $P_2$  denote the drop probability of class 1 and class 2 respectively. The results show that in respect of the VCR threshold, the overall drop

probability is the same even though different threshold values cause service differentiations to vary. In fact, the overall drop probability is the exact same expression obtained from the Erlang B formula [14]. For a three-class system, the analytical part is too tedious to show in the thesis, but it can be verified by using the procedures described in Appendix B with different set of thresholds, then comparing the overall drop probability.

Among the various schemes reviewed in the introduction, the overall drop probability of JET QoS scheme only approaches the classless drop probability under high traffic intensity, which is verified in [15], while intentional dropping scheme such as GC scheme does not conform to the Conservation Law.

Table 1. Computational drop probability, with total 2 channels

Threshold	Burst Drop probability	
0	$P_1$	$\frac{(\lambda_1 + \lambda_2)^2}{(\lambda_1 + \lambda_2)^2 + 2\mu(\lambda_1 + \lambda_2 + \mu)}$
	$P_2$	$\frac{(\lambda_1 + \lambda_2)^2}{(\lambda_1 + \lambda_2)^2 + 2\mu(\lambda_1 + \lambda_2 + \mu)}$
	$P_{overall}$	$\frac{(\lambda_1 + \lambda_2)^2}{(\lambda_1 + \lambda_2)^2 + 2\mu(\lambda_1 + \lambda_2 + \mu)}$
1	$P_1$	$\frac{\lambda_1 \left( (\lambda_1 + \lambda_2)^2 (\lambda_1 + 2\lambda_2 + 4\mu) + (\lambda_1 + \lambda_2) (2\lambda_2\mu + 4\mu^2) + 4\lambda_2\mu \right)}{\left( (\lambda_1 + \lambda_2 + \mu)^2 + \mu^2 \right) (\lambda_1^2 + 2(\lambda_2 + 2\mu)(\lambda_1 + \mu))}$
	$P_2$	$\frac{(\lambda_1 + \lambda_2)^2 (\lambda_1^2 + 2\lambda_1\lambda_2 + 4\mu^2) + 4\lambda_1\lambda_2\mu^2 + 2(\lambda_1 + \lambda_2)\mu(2\lambda_1^2 + 4\lambda_1\lambda_2 + \lambda_2^2)}{\left( (\lambda_1 + \lambda_2 + \mu)^2 + \mu^2 \right) (\lambda_1^2 + 2(\lambda_2 + 2\mu)(\lambda_1 + \mu))}$
	$P_{overall}$	$\frac{(\lambda_1 + \lambda_2)^2}{(\lambda_1 + \lambda_2)^2 + 2\mu(\lambda_1 + \lambda_2 + \mu)}$
2	$P_1$	$\frac{\lambda_1^2}{(\lambda_1 + \mu)^2 + \mu^2}$

### Chapter 3 Theoretical Analysis

	$P_2$	$\frac{(\lambda_1 + \lambda_2)^3}{\lambda_2((\lambda_1 + \lambda_2 + \mu)^2 + \mu^2)} - \frac{\lambda_1^3}{\lambda_2((\lambda_1 + \mu)^2 + \mu^2)}$
	$P_{overall}$	$\frac{(\lambda_1 + \lambda_2)^2}{(\lambda_1 + \lambda_2)^2 + 2\mu(\lambda_1 + \lambda_2 + \mu)}$

## Chapter 4

# VCR Performance for the Single Node Scenario

In this chapter we study the performance of VCR for a two-class and a three-class single-node system given a QoS requirement in terms of *burst drop probability*, which is defined as the ratio of the number of dropped bursts to the total number of generated bursts.

For the single node scenario, we consider an OBS switching node with  $T$  numbers of WDM channels per output link where  $T$  varies from 4 to 32 depending on the purpose of the simulation. Bursts and corresponding headers are generated according to Poisson process. Burst length is exponentially distributed, and a mean burst length of  $1/\mu$ , 10ms, is set for all priority classes. We assume that a bufferless OBS network. The transmission rate at the switching node is set at 10 Gb/s.

### 4.1 Conformance of VCR to Conservation Law

In chapter 3.3, we have proved that VCR conforms to Conservation Law, also we demonstrate that the overall drop probability of a two-class two-channel VCR system matches to the Erlang B formula through analysis. Hence the same result is applicable to multi-class and multi-channel system. Therefore, in this chapter, we verify this in a 16 channel system by comparing the overall drop probability obtained from Erlang B formula with that of the simulation results in both two-class and three-class systems,



under varying load conditions and threshold values. The result of the comparison is a perfect match, as shown in Figure 3. We define the load for each priority class (denoted by  $\rho_i$ ) in this thesis as  $\lambda_i/\mu$ , hence the overall load  $\rho = \sum \rho_i = \sum \lambda_i/\mu$ , since the same service rate  $\mu$  is assumed for each class. The overlapping lines in the Figure 4.1 further confirm the conservative property of VCR both by simulation and computation.

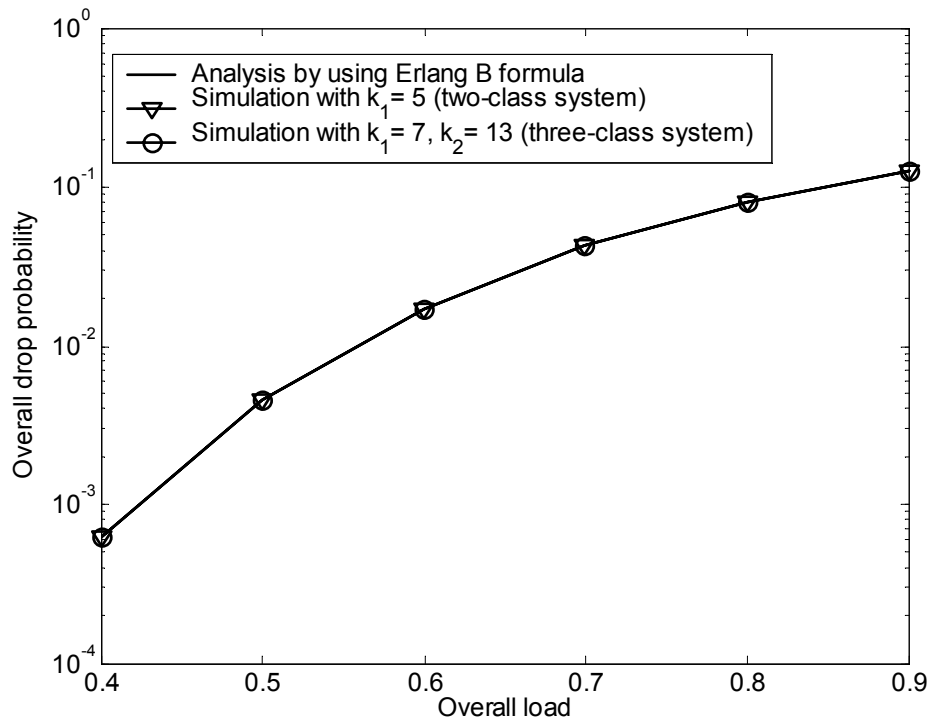


Figure 4.1 Computational and simulation comparisons

To further demonstrate the conformance of VCR to Conservation Law through simulations, two rounds of simulations are conducted, in a two-class and a three-class system, respectively, to compare the overall drop probability under the same load condition but different QoS requirements. The load is assumed to be 0.7 in both simulations.

In two-class system, the QoS requirement of Class 1 burst is assumed to vary between  $1e-05$  and  $1e-02$ ; the arrival rate of class 1 bursts is assumed to be half of

that of class 2 bursts. Figure 4.2 shows the comparison of VCR with GC. It can be found that the overall drop probability of VCR is constant for all the QoS requirements. However, the overall drop probability of GC is much higher than that of VCR and decreases as the QoS requirement decreases (i.e. the value of QoS drop probability increases).

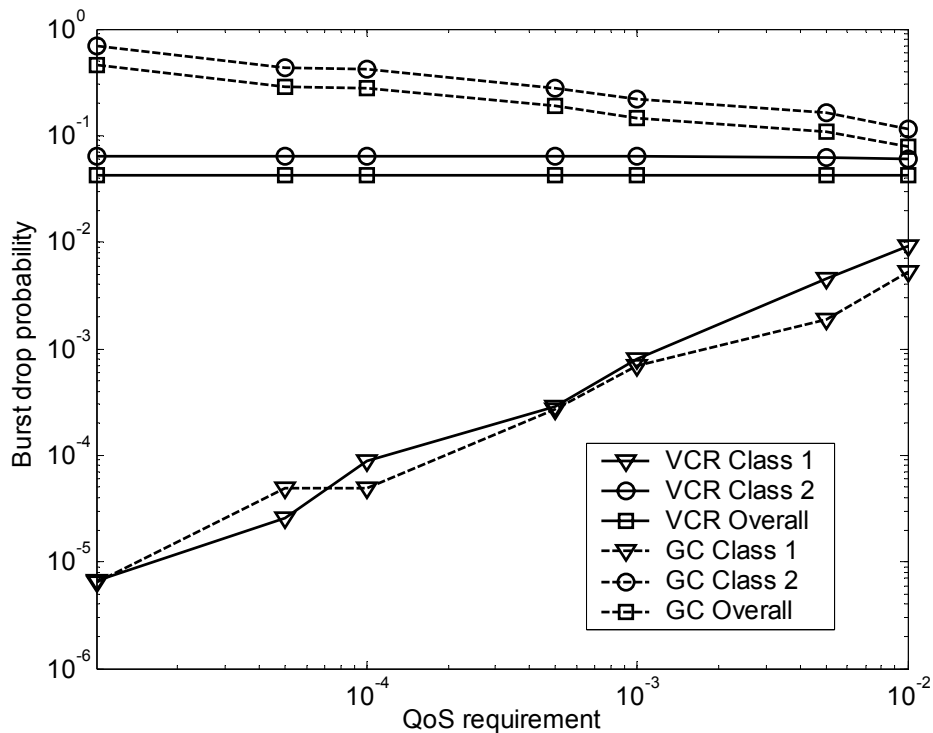


Figure 4.2 Drop probability vs. Class 1 QoS requirement for two-class system

The simulation in a three-class VCR system is conducted with the assumption that the Class 2 burst QoS requirement varies between  $3e-04$  to  $0.1$  and the Class 1 QoS requirement is the same as in the two-class case. As expected, Figure 4.3 shows exactly the same overall drop probability of VCR as in the two class case.

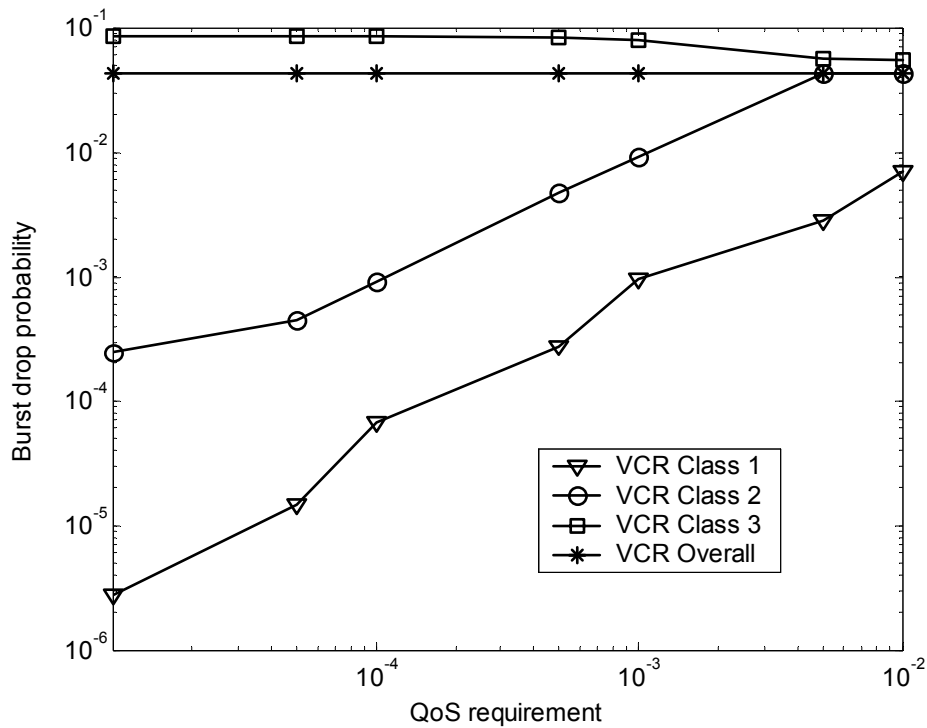


Figure 4.3 Drop probability vs. Class 1 QoS requirement for three-class system

In order to further verify that VCR conforms to Conservation Law at different numbers of channels system, more simulation results for the channel number of 4, 8, 16 and 32 are illustrated in Figure 4.4. As expected, a straight line is shown in each of the graph.

Based on the above simulations, it is observed that under the same load condition and the same number of channels, the overall drop probability of VCR remains constant, regardless of the QoS requirement and the number of traffic classes. Therefore, the overall drop probability of VCR will always be lower than that of other QoS schemes which do not conform to Conservation Law.

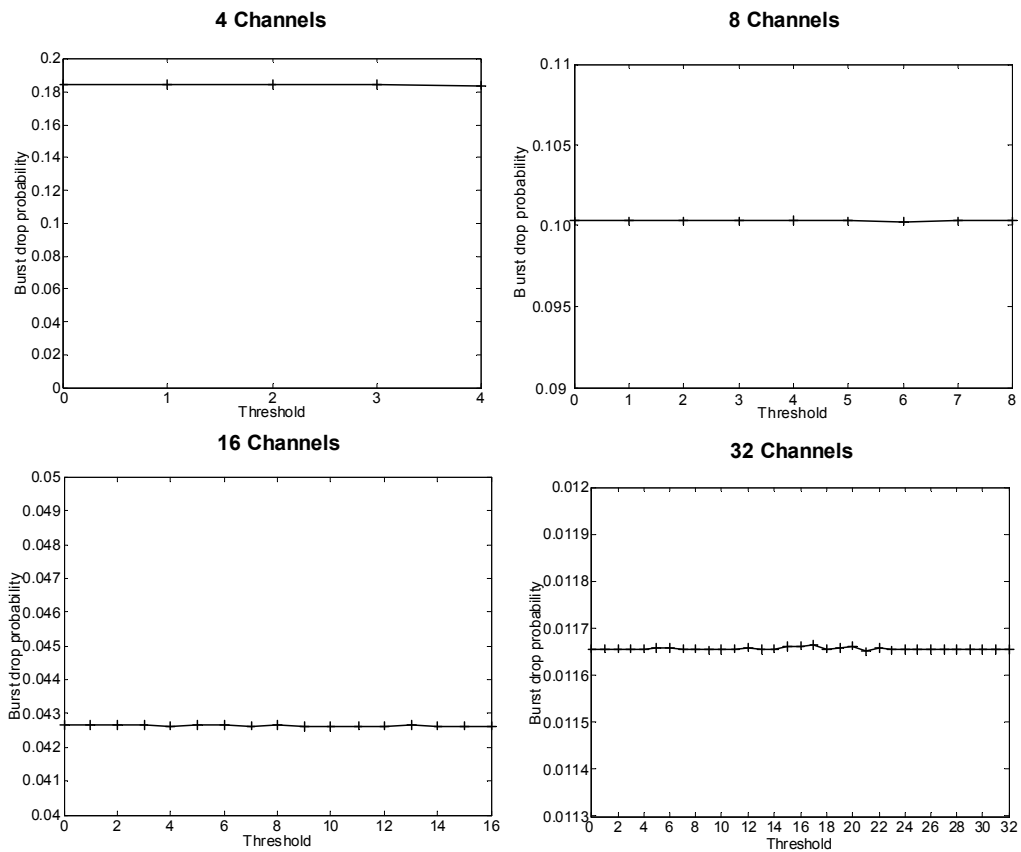


Figure 4.4 Overall drop probability of VCR vs. Threshold

## 4.2 Comparison of the Two-Class System with JET QoS and GC schemes

In all simulation studies involving the two-class system, the arrival rate of high priority traffic is assumed to be half of the low priority traffic. VCR is compared with the JET QoS scheme and the GC scheme.

### 4.2.1 Comparison with JET QoS

JET QoS is a well studied service differentiation scheme for OBS networks. It is difficult to compare the performances of VCR with JET QoS since the schemes measure QoS differently. VCR is an absolute QoS mechanism, while JET QoS offers

relative QoS by allocating higher offset times to higher priority bursts. However, a comparison is still possible as follows: first, we obtain the best service differentiation of JET QoS, achieved at a near 100% class isolation when the extra offset time is set to be five times the mean burst length, as stated in [15]; the achieved class 1 drop probability of the JET QoS scenario (obtained via simulation) is then given to VCR as the absolute QoS requirement for its class 1 traffic. Based on this particular QoS requirement at load conditions between 0.4 to 0.9, the VCR threshold setting can be obtained by implementing the threshold calculation algorithm. It was determined that the threshold setting was evaluated to be 16 for all loads. The drop probabilities of these two schemes are then compared as shown in Figure 4.5. Simulation results show that VCR is able to achieve the QoS requirement set by the JET QoS scheme (i.e. at 100% class isolation), however, the class 2 and overall drop probability of VCR is lower than JET QoS. This means that VCR can achieve the same degree of class isolation as JET QoS, but VCR utilizes the bandwidth more efficiently than JET QoS. The superiority of VCR drop probability is expected since VCR is demonstrated to conform to the Conservation Law. The JET QoS scheme does not conform to the Conservation Law in general. At best, JET QoS only approaches the Conservation Law only at the high loading conditions [15].

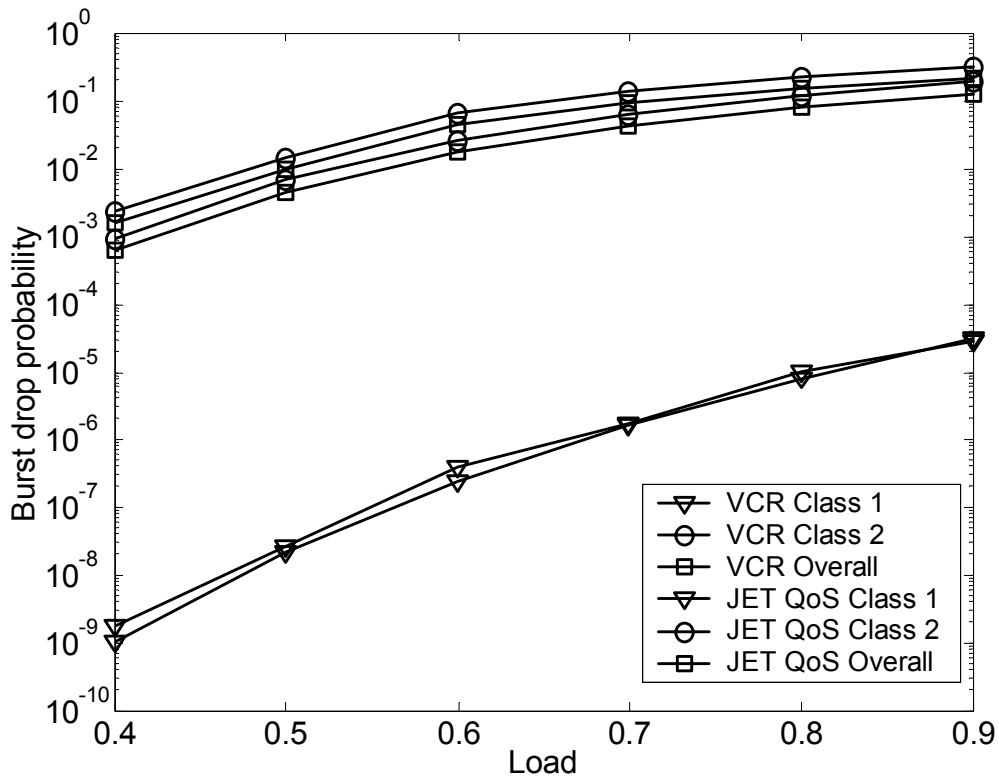


Figure 4.5 Comparison of VCR with JET QoS in a single node scenario

#### 4.2.2 Comparison with GC

We assume the absolute QoS requirement for class 1 (high priority class) is  $P_{1\_QoS} = 1e-04$ . First, we obtain the thresholds for two schemes under different load conditions. The results are shown in Table 2. The VCR thresholds are calculated by using the threshold calculation algorithm listed in Figure 3.1, while those of GC are based on the analysis in [11]. In order to yield the same QoS drop probability, GC generally requires lower thresholds than VCR does, as we can see in Table 2. This is because the GC scheme exclusively reserves the threshold number of channels for higher priority traffic while VCR does not exclusively reserve channels for the higher priority traffic as explained in Chapter 2.

Table 2. Thresholds in two-class system for absolute QoS,  $P_{1\_QoS} = 1e-04$

Load	0.4	0.5	0.6	0.7	0.8	0.9
VCR Threshold	8	11	12	13	14	15
GC Threshold	2	4	5	7	8	9

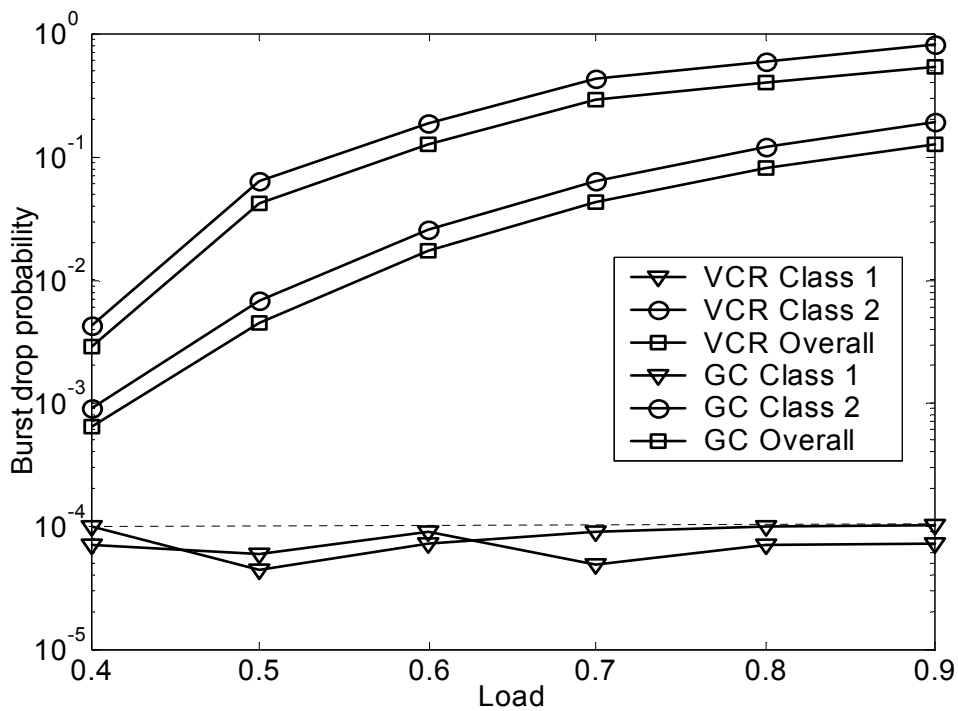


Figure 4.6 VCR vs. GC in a single node scenario

Figure 4.6 shows the individual drop probabilities of the two priority classes and the overall drop probability. It can be observed that both VCR and GC are able to meet the burst dropping requirements of class 1 (higher priority class)  $P_{1\_QoS} = 1e-04$ , though GC registers a significantly higher class 2 drop probability and thereby, a higher overall drop probability than VCR. These results are expected due to the non-conformance of the GC scheme to the Conservation Law, while in contrast, the VCR scheme conforms to the Conservation Law.

### 4.3 Performance evaluation of the three-class system

The performance of VCR in a three-class scenario is now presented. We first set the absolute QoS drop probabilities for class 1 and class 2 traffic to be  $P_{1\_QoS} = 1e-04$  and  $P_{2\_QoS} = 1e-03$ , respectively. We also assume that 1/6 of the overall traffic belongs to class 1, 2/6 to class 2, and the remaining 3/6 to class 3. All other assumptions remain as before. Table 3 lists the VCR thresholds for the two higher priority classes when overall load varies from 0.4 to 0.8.

Table 3 VCR thresholds for a three-class system to achieve absolute QoS requirements;  $P_{1\_QoS} = 1e-04$  ;  $P_{2\_QoS} = 1e-03$

Load	0.4	0.5	0.6	0.7	0.8
Threshold 1	5	7	8	9	10
Threshold 2	0	8	10	11	14

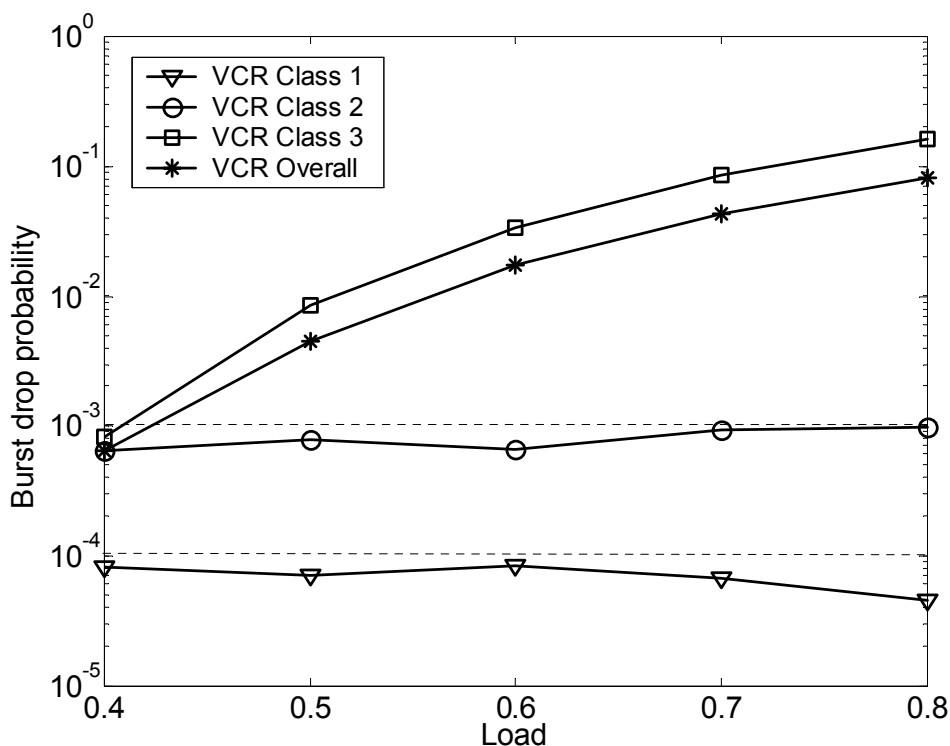


Figure 4.7 VCR drop probability vs. load in the three-class system



Figure 4.7 displays the individual drop probability of each priority class and the overall drop probability, obtained through simulations. The dotted line denotes the absolute QoS requirement for class 1 and class 2. It is clear that using the VCR thresholds determined by the threshold calculation algorithm, VCR is able to meet respective QoS requirements for the two higher priority classes.

# **Chapter 5** **I-**

## **header and VCR Performance for the Multi-node Scenario**

This chapter evaluates VCR in a more practical multi-node scenario. The multi-node network model consists of a collection of core nodes and edge nodes, connected as shown in Figure 5.1. The edge nodes accumulate traffic from multiple client networks and assemble it into bursts, which are then transmitted to the high capacity core network; on the other hand, upon receiving data bursts, the edge nodes pass them to the intended client networks based on their destination information. In the core network, data bursts go through an all-optical path from source to destination. In this thesis, we define a traffic flow as a collection of all the bursts that have the same entry and exit points in a network segment. We shall study VCR performance in this chapter by assuming multiple traffic flows in this network model.

We also make the following assumptions applied to all our simulations in the multi-node OBS network scenario:

- Burst lengths are exponentially distributed with the same average burst length for all flows;

- The same transmission rate is used at each core node;
- The number of wavelength per link is 16;
- Every core node is bufferless;
- $\Delta$ , the maximal header processing delay at each node, is set at  $10\mu\text{s}$  in all the simulations.

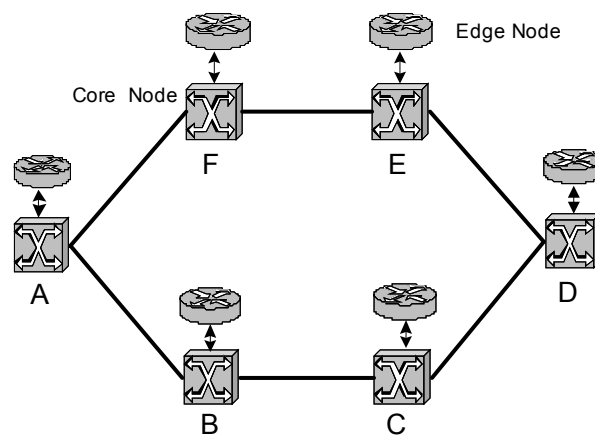


Figure 5.1 An OBS network model

## 5.1 Weakness of VCR in multi-node networks

It is perceivable that when the VCR scheme is implemented at each core node in an OBS network, bandwidth may be wasted in downstream nodes. This is demonstrated in a simple example, where a total of three flows go through the network segment in Figure 5.1. For ease of exposition, we assume that Flow 0 (F0) traverses all 5 hops in anticlockwise direction from node A to Node F, and Flow 1 (F1) and Flow 2 (F2) are 1-hop anticlockwise flows, entering at nodes B and E and exiting at nodes C and F respectively. For simplicity, let us further assume that traffic in both F0 and F2 are low

priority, while the traffic in F1 is high priority. Now, some undesired situations can arise as follows:

For example, at Node B, a high priority header from F1 can preempt a time period reserved by a low priority header from F0, if it needs to. However, the header of that particular low priority burst of F0 has already proceeded on to downstream nodes C, D, E, F and has successfully gained time slot reservations in these nodes. Unfortunately, those reserved time slots, or bandwidth, will not be utilized since the low priority burst will never arrive. Consequently, low priority bursts from F2 may be denied from reserving the channels, which are allocated to the F0 burst, which will never arrive. Such a waste in bandwidth inevitably affects the drop probabilities of F2.

Although we have used a much simplified network case for demonstration purpose, similar scenarios can occur in networks of more generic topologies.

## **5.2 The i-header mechanism**

Based on the aforementioned example, we realize that such wastage could be avoided if the preemption of a low priority burst at an upstream node can also propagate to downstream nodes as well. That is to say, when a high priority burst from F1 preempts a low priority burst from F0 at node B, the reservations made by the same low priority burst at nodes C to F should also be cancelled. By doing so, those reserved time periods can be released and made available for other bursts, and consequently such bandwidth wastage can be avoided. In order to achieve this, it is clear that the downstream nodes must be informed of the preemptions that had succeeded at

upstream nodes. Therefore, in addition to normal control headers for low priority bursts, we propose to adopt a new type of control packet, *informing header (i-header)*, which is released to the downstream nodes by an upstream node in the event of a low priority burst preemption. To differentiate i-headers from normal headers, we use a one-bit field in all headers to indicate its type. In the rest of this section, we shall discuss how i-headers can help VCR improve the drop probabilities of the two-class system and the three-class system in OBS networks. The idea can be easily extended to the multi-class system.

The selection of the low priority burst, which is to be preempted, can be done in a few ways. It can be based on minimizing the accumulated length of the preempted bursts. Random selection is also a reasonable choice if simplicity is an important consideration. The selection criterion used in our simulation is to reduce the effect of preemption on other traffic served by downstream nodes; hence the burst with the latest starting time is preferred. This is based on the fact that in a multi-node system, the offset time between the control header and the actual burst gets shorter and shorter due to header processing delay introduced at each node while the header travels along its route. Preempting the burst with the latest starting time therefore maximizes the chance to successfully revoke the reservations made at all the downstream nodes.

An i-header is generated by any core node where preemption happens. In some sense, the i-header can be considered as a replication of the header of the preempted burst except that the one-bit field is changed to indicate its status as an i-header. It carries information about the preempted burst, such as the starting time, the burst length, the source and destination, as well as the output from the core node.

The i-header then traverses the same route as the normal header of the pre-empted burst. Since the event of burst preemption always occurs before a burst has completed, the network topology and the policy for these routing headers should not change. Thus these are two possible scenarios when an i-header reaches a downstream core node:

Scenario 1: The core node successfully finds out the reserved time slot based on the information that the i-header carries, and cancels the reservation. If the i-header has not reached its destination, the node updates its information and passes the i-header on to the next node; else it will simply drop the i-header.

Scenario 2: The core node cannot find the reserved time slot. It may be caused by the following reasons. If such cases happen, there is no need to continue transmitting the i-header. It will simply be dropped.

- 1) The arrival time of the i-header is later than the start time of the particular low priority burst transmission; or
- 2) The time slot has been released by another i-header; or
- 3) The reserved time slot has been already preempted by another high priority header also transmitted by this node.

When preemption happens, the core node sends the generated i-header first, and the high priority header second. The reason is as follows. Supposing the high priority header continues on its way ahead of the generated i-header, chances are the high priority header will find that all channels are again fully occupied at a downstream node, and another preemption is then triggered. If this downstream node happens to lie

on the routes of both the high priority header and the preempted low priority header, the preemption will result in one of two possible scenarios. The desirable scenario is that the reservation made by the same low priority header is revoked, while the undesirable scenario is that a reservation made by some other burst is preempted, which is possible since the high priority header itself does not know which low priority header it has preempted in the previous node. In the undesirable scenario, the reservation made by the same low priority header should have been preempted. Instead it remains, wasting precious bandwidth. Therefore, the i-header, which has the knowledge of the preempted low priority header, should always be sent out first since it will clear the way for the high priority header by revoking reservations made by the same low priority header.

### **5.3 Performance improvements in a multi-node scenario with i-header**

In this chapter, we study through simulation the performance improvement of VCR with the introduction of the i-header mechanism in a two-class system. The simulations will show that the flows that benefit more from i-headers are those long hop flows and flows that are found furthest downstream. Relevant reasons and explanations will be provided. We now call the improved scheme VCR-I hereafter. The improvement (in percentage) is quantitatively defined in Equation (9). The same network model in Figure 10 is used, and in order to evaluate how single hop flows affect multi-hop flows, five traffic flows are assumed. Flow 0 is an anticlockwise 5-hop flow from Node A to Node F, while the other four flows are anticlockwise single

hop flows, Flow 1 to Flow 4, starting from Nodes B, C, D, and E respectively and exiting at Nodes C, D, E, and F respectively. We also assume that in each traffic flow, 1/3 of overall traffic belongs to high priority class and 2/3 belongs to low priority class. Each transmission link consists of 16 channels. Both burst length and interarrival time are assumed to be exponentially distributed.

$$\text{Improvement} = \frac{(\text{Drop}_n - \text{Drop}_i)}{\text{Drop}_n} \times 100 \% \quad (9)$$

$\text{Drop}_n$  Drop probability without i-headers

$\text{Drop}_i$  Drop probability with i-headers

We study the drop probability improvements of VCR-I over VCR under different load conditions. The range of traffic load for each node is chosen to be from 0.2 to 0.9. Different flows are assumed to generate bursts at the same rate. Since each link is shared by two flows, each flow is assumed to provide half of the overall load. The initial offset time between a header and data burst for each flow is set as  $\Delta \bullet H$ , where  $H$  is the number of hops along the route of the flow. The VCR threshold for each node is assumed to be the same, which is identically set to 13 channels.

Figure 5.2 illustrates the performance improvement in drop probabilities for the various flows when the i-header mechanism is implemented. In Figure 5.2(a), only when the overall load is above 0.6, there is some improvement on high priority drop probability of VCR-I. This is because: as the traffic intensifies, it is more likely for high priority bursts to reach the threshold. In the absence of i-headers, later arrival high priority headers may be dropped, if all channels are fully occupied and the threshold has been reached. On the contrary, a preceding i-header may very likely

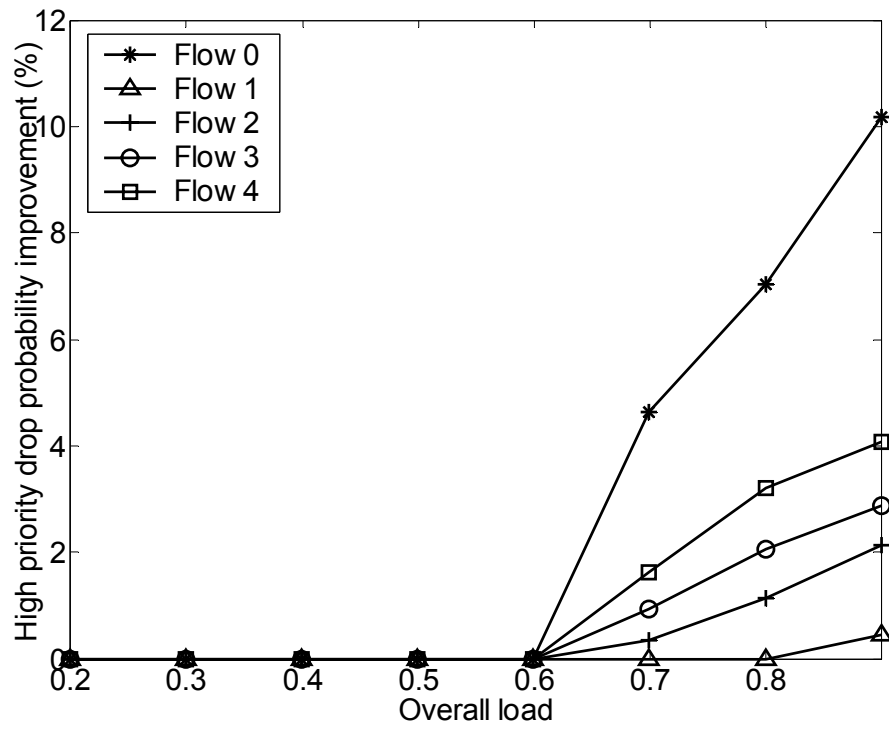


cancel the reservation made by a low priority header, thus rendering the channel available for the later arriving high priority burst.

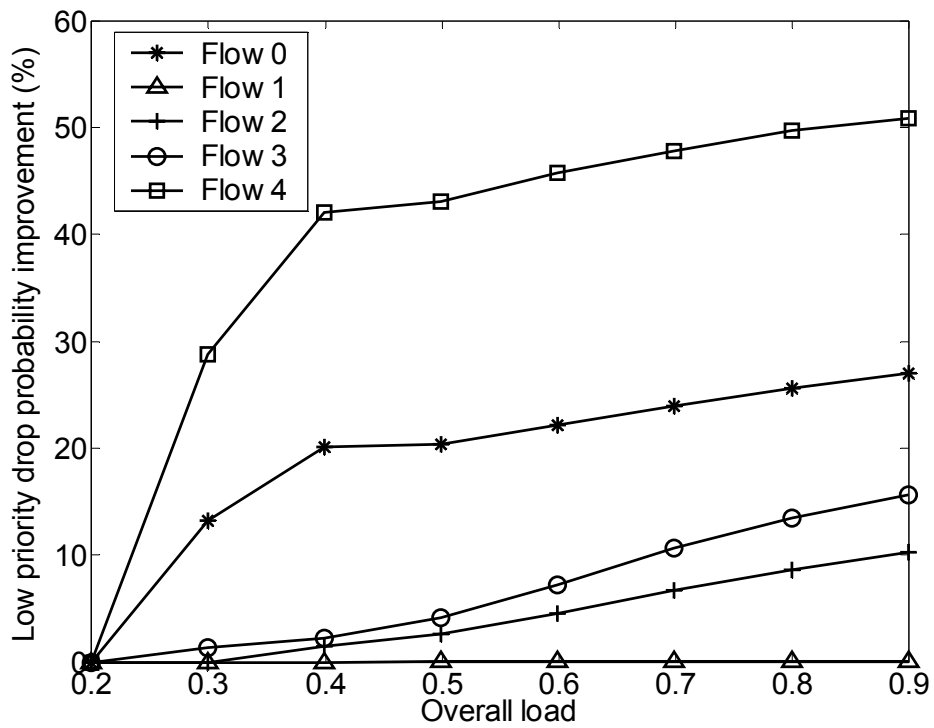
The performance improvement for low priority classes is shown in Figure 5.2(b). Flow 4 has the most significant improvement in terms of burst drop probabilities. This is expected. The drop probabilities of Flow 4 are largely affected by Flow 0, which is the only flow that shares the link with it. Consider what happens when a low priority burst from Flow 0 gets preempted by a high priority burst. The generated i-header will try to cancel all reservations made by the low priority header on all remaining links, including the one that Flow 4 passes. As this happens for all preemptions that occur ahead of Flow 4, the significant improvement on Flow 4 can thus be seen as an accumulated effort of all i-headers generated by all other flows.

On the other hand, Flow 1 enjoys minimum performance gains in both high and low priority classes. Given its relative upstream position in the network segment, none of the i-headers generated by Flow 2, 3, 4 can have any positive impact on it.

As a multi-hop flow in this network case, Flow 0 plays an important role in the simulations. The higher its load is, the more often its low priority bursts will be preempted and hence the lower the burst dropping count will be with i-header mechanism.



(a) Performance improvement of high priority class



(b) Performance improvement of low priority class

Figure 5.2 Performance improvement of VCR-I vs. VCR

## 5.4 Performance comparison of VCR, VCR-I with other QoS schemes in a multi-node Scenario

In this chapter, the absolute QoS performance of VCR and VCR-I in the OBS network model is investigated. In this study, we intend to guarantee end-to-end drop probability for the prioritized traffic by implementing VCR at each core node. To do this, we need to translate the QoS requirement for the entire network into more concrete requirements. Specifically, at each node, we determine the individual QoS drop probability requirement for each traffic class based on the QoS requirement for the entire network. Let us assume that each higher priority class  $i$  has an end-to-end QoS requirement of  $P_i^{NET}$ . Based on the network diameter, we can determine the upper bound of drop probability for each class at every node. Let  $D$  be the network diameter, which is the maximum number of hops between any source-destination pair. Let  $P_i^{NODE}$  be the QoS requirement at each node for class  $i$ . To guarantee end-to-end dropping for the longest path in the network with  $D$  hops, we have:

$$P_i^{NET} = 1 - (1 - P_i^{NODE})^D \quad (10)$$

Therefore, 
$$P_i^{NODE} = 1 - e^{(\ln(1 - P_i^{NET}))/D} \quad (11)$$

If the drop probability  $P_i^{NODE}$  can be guaranteed at every node along the path, then the end-to-end drop probability  $P_i^{NET}$  will be guaranteed for all flows in the OBS network. This relationship is applicable if the arrival traffic to each node is exponentially distributed and independent of each other. To simulate a more generic network scenario, which satisfies the above assumptions, we set six traffic flows in the network shown in Figure 5.1. Each flow starts from a different source core node and

traverses five hops in an anticlockwise direction. The paths of the six flows are hence as follows:

Flow 1: A->B->C->D->E->F;

Flow 2: B->C->D->E->F->A;

Flow 3: C->D->E->F->A->B;

Flow 4: D->E->F->A->B->C;

Flow 5: E->F->A->B->C->D;

Flow 6: F->A->B->C->D->E

By definition, therefore, the diameter of this OBS network is  $D=5$ .

### 5.4.1 Two-class system

#### 5.4.1.1 Comparison with the JET QoS scheme

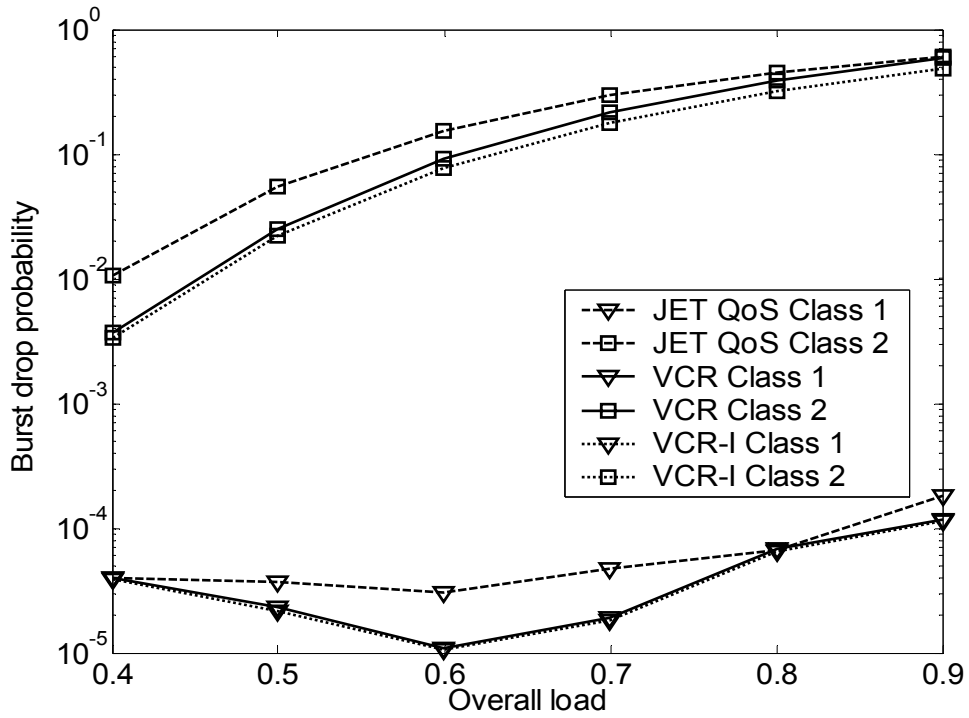
To set a base for the comparison between the VCR scheme and the JET QoS scheme, we have to ensure that both QoS schemes produce the same QoS levels. To achieve this end, we simulated the JET QoS scheme under 100% class isolation between the two classes and then obtain the end-to-end drop probabilities. Table 4 lists the high priority burst drop probability of JET QoS, obtained via simulation. The  $P_1^{NET}$  values in Table 4 are then assigned to be the QoS requirements for the VCR and VCR-I schemes to achieve. The overall load per link varies from 0.4 to 0.9, which is evenly distributed between the six flows sharing a transmission link. The base offset time is set to be  $5\Delta$  for the all six flows. To fulfill the particular requirement at each load,

VCR threshold values are obtained using the threshold calculation algorithm of Figure 3.1, as shown in the last row of Table 4.

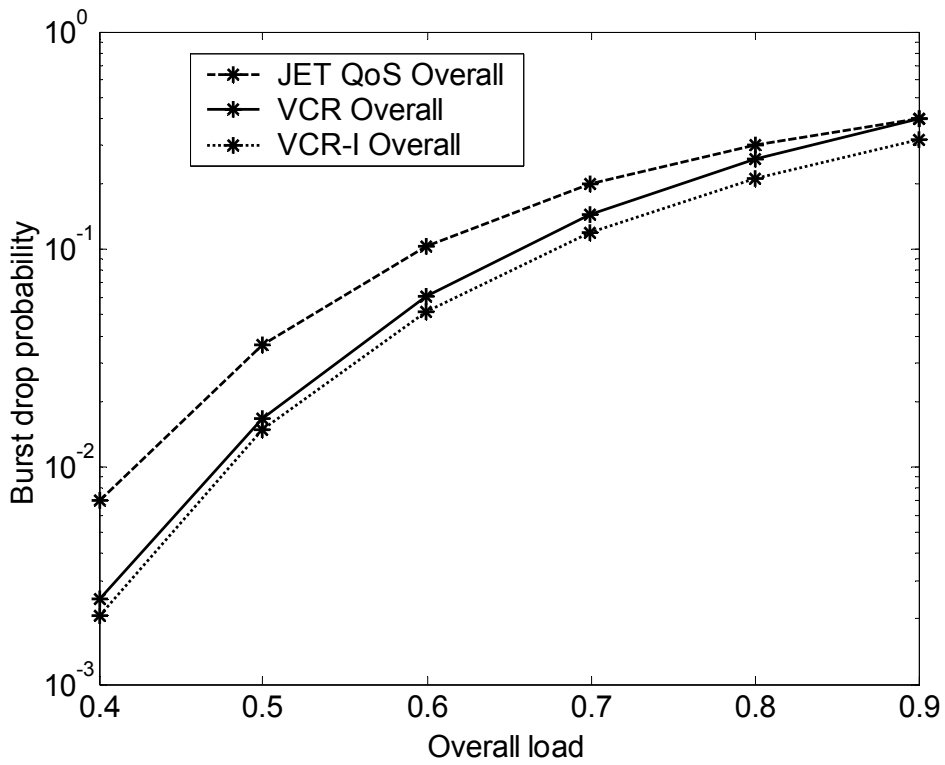
Table 4 QoS requirement and Threshold settings for VCR and VCR-I in two-class system

<b>Load</b>	0.4	0.5	0.6	0.7	0.8	0.9
$P_1^{NET}$	3.88e-05	3.89e-05	3.85e-05	4.79e-05	6.67e-05	1.84e-04
<b>VCR Threshold</b>	10	12	14	15	15	16

Figure 5.3 (a) shows the aggregate drop probabilities of all flows for various priority classes and for each QoS schemes. It is clear that the VCR and VCR-I schemes are able to achieve the QoS requirements provided by the JET QoS scheme (i.e. 100% class isolation). As we have discussed in the last section, the most significant improvement by adopting i-headers in VCR scheme is experienced on the low priority class, class 2. The class 2 drop probability of VCR is much lower than that of JET QoS under lightly loaded conditions. When the load increases, however, the class 2 drop probability of VCR approaches to that of JET QoS. On the other hand, with the help of i-headers, VCR-I easily outperforms JET QoS with lower drop probabilities regardless of the load condition. It is clear that the conformance to Conservation Law in the VCR scheme brings with it the advantage of minimizing drop probabilities in all priority classes even in a multi-node scenario.



(a) High and low priority classes



(b) Overall drop probability

Figure 5.3 VCR and VCR-I vs. JET QoS in a multi-node scenario

Figure 5.3 (b) illustrates the overall drop probabilities of all the priority classes in all the flows in a multi-node scenario. VCR scheme and VCR-I scheme both outperform the JET QoS scheme in overall drop probability of all six flows, when the load is below 0.9. Under light load conditions, VCR can achieve a drop probability which is up to 80% lower than that of JET QoS. When the system is heavily loaded, however, the bandwidth wastage caused by preemption begins to take its toll, raising its drop probabilities to approach that of the JET QoS scheme. However the application of i-headers helps VCR-I register a lower overall drop probability than JET QoS throughout all load conditions. More specifically, when the load is 0.9, VCR-I yields an overall drop probability 15% lower than those of VCR and Jet QoS. In real OBS networks, loading rarely exceeds 0.8. It is clear that VCR alone is able to provide more efficient QoS differentiation than JET QoS under practical loading conditions in a multi-node scenario.

While i-headers are helpful in reducing bandwidth wastage, some extra overheads are required, namely, the generation of additional number of control headers. The overhead is measured in our simulations as the percentage of the number of generated i-headers over the total number of normal control headers for all flows. Results indicate that the overhead is usually below 6%. Considering the relatively small size of control headers compared with data bursts, the actual overhead is insignificant. Given that the overall drop probability of VCR-I is 14%-30% lower than that of VCR, the overhead is clearly worth its price.

#### 5.4.1.2 Comparison with the GC scheme

For comparisons with the GC scheme, we assume that the guaranteed QoS drop probability for class 1 traffic in the entire network is  $1e-03$ . Based on Equation (11), the class 1 QoS requirement for each node works out to be  $2e-04$ . The threshold settings for VCR and VCR-I under different load conditions, are also calculated, as well as thresholds used by GC. The burst arrival rate ratio between class 1 and class 2 is set to be 1:2. The offset time of each flow is  $5\Delta$ . Our simulation studies focus on the overall drop probability of all six flows. The overall, class 1 and class 2 drop probabilities of the three schemes are shown in Figure 5.4, where it can be observed that the class 1 burst drop probabilities of all three schemes are lower than the given QoS requirement. The additional header introduced in VCR-I, i-header, however, improves both the overall drop probability performance and the drop probability performance of each class. The heavier the load, the more significant the improvement is, particularly in the class 2 and overall drop probabilities. Although the GC scheme is able to meet the QoS requirement, it yields the highest overall and class 2 drop probability among the three schemes. The GC scheme cannot match the performance of VCR or VCR-I which obey the conservation Law on drop probabilities.



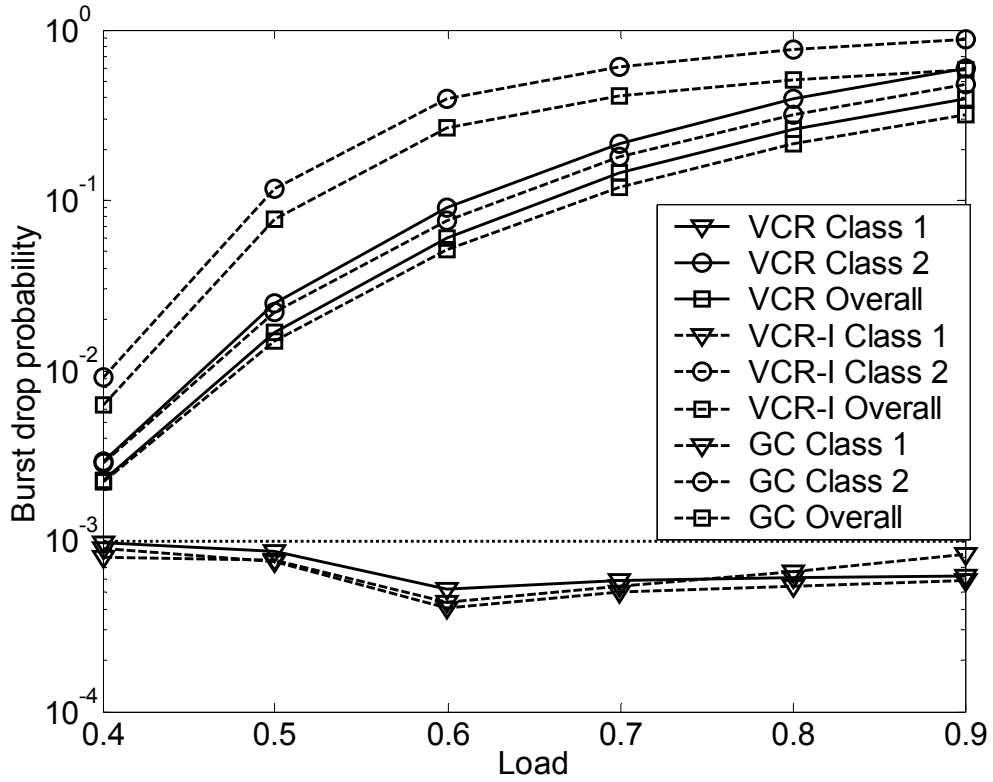


Figure 5.4 VCR and VCR-I vs. GC in a multi-node scenario

### 5.4.2 Three-class system

A three priority class performance evaluation of VCR and VCR-I in the usual 6 flows multi-node scenario is now presented. We assume class 1 QoS requirement for the entire network to be  $P_1^{NET} = 1e-03$ , and class 2  $P_2^{NET} = 1e-02$ . Based on Equation (11), the class 1 and class 2 QoS drop probability for each node are  $P_1^{NODE} = 2e-04$  and  $P_2^{NODE} = 2e-03$ , respectively. We further assume that the load distribution ratio of three classes for each flow is 1:2:3, in the descending order of traffic priority. The offset time setting for all flow is  $5\Delta$ . Using the threshold calculation algorithm for load ranging from 0.4 to 0.9, appropriate VCR threshold settings are generated. Figure 5.5 illustrates the combined drop probabilities of all six flows for the various priority

classes. Clearly, in the Figure 14, both VCR and VCR-I meet the QoS requirement for each priority class. This verifies our three-class theoretical contributions on VCR and demonstrates the usefulness of the VCR scheme for providing absolute QoS in a multi-node network.

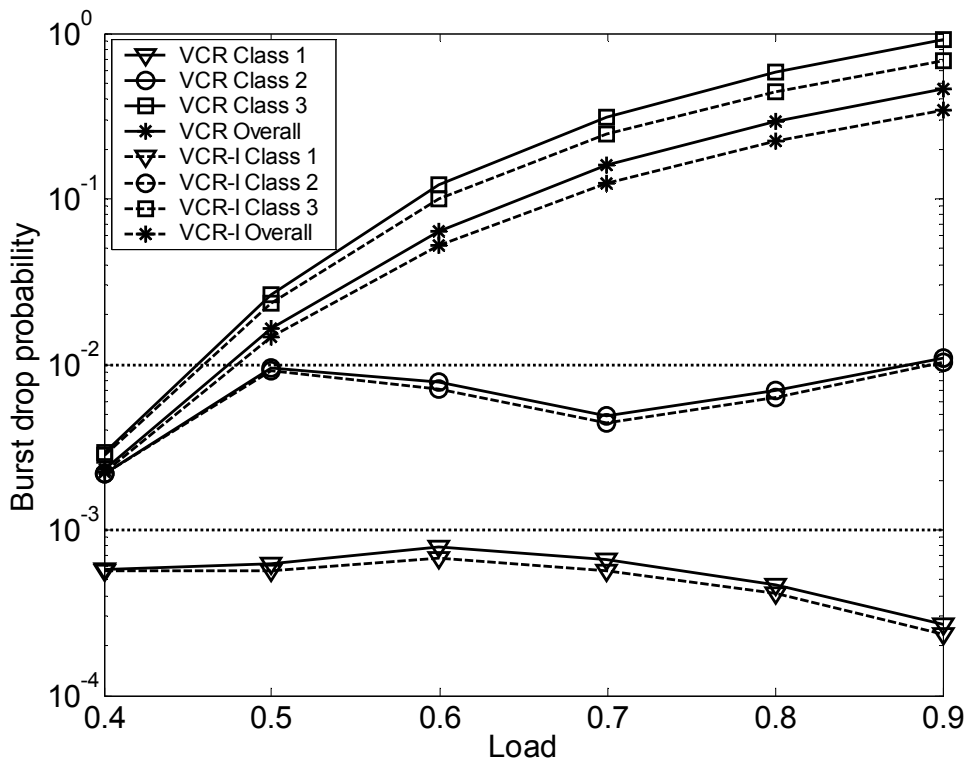


Figure 5.5 VCR Drop probability for absolute QoS in a three-class system

## Chapter 6

### Conclusion

The provision of quality of service guarantees has become an increasingly important and challenging topic in the design of OBS networks. In this thesis, we have contributed a new and novel channel reservation scheme, known as VCR. The scheme relies on virtual channel reservation and preemption. The analysis demonstrates that VCR can provide absolute QoS differentiation in OBS networks, while maintaining conformance to the Conservation Law. The conformance to Conservation Law minimizes the drop on lower priority bursts serviced by the node. This important property is absent in many QoS schemes like GC and JET QoS. The bandwidth wastage problem encountered by downstream nodes due to VCR's preemptive mechanism in a multi-node OBS network has also been addressed, in the form of an i-header solution. Extensive simulation results conducted in a variety of scenarios, eg. single-node, multi-node, two-class, three-class not only verify our theoretical analysis but also demonstrate the superiority and convenience of VCR (with or without i-header) for providing absolute QoS differentiation compared to other schemes like GC or JET QoS. VCR has also been verified to conform to the Conservation Law in single-node cases, which means VCR can provide the same overall dropping probability regardless of the degree of service differentiation and the absolute QoS requirements for higher priority classes. Thus VCR promises a lower overall dropping probability

than schemes that do not conform to the law. This is proven through simulations in single-node cases by comparing VCR with another channel reservation scheme, GC in particular, which is proposed in electronic networks but is also applicable to OBS networks. The comparisons indicate that VCR is able to meet the QoS requirement while utilizing the bandwidth more efficiently than GC does.

## Bibliography

- [1] J. Turner, "Terabit Burst Switching", *Journal of High Speed Networks*, vol. 8, pp.3-16, 1999.
- [2] C. Qiao and M. Yoo, "Optical Burst Switching (OBS) - A New Paradigm for an Optical Internet", *Journal of High Speed Network*, vol. 8, pp. 69-84, 1999.
- [3] C. Qiao and M. Yoo, "Choices, Features, and issues in optical burst switching", *Optical Network Magazine*, April 2000.
- [4] Y. Xiong, M. Vandenhoute, and C. Cankaya, "Control architecture in optical burst-switched WDM networks", *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS* 2000.
- [5] C. Muthy and M. Gurusamy, "WDM Optical Networks: Concepts, Design, and Algorithms", Prentice Hall 2002.
- [6] R. Braden, D.Clark, and S. Shenker, "Integrated Service in the Internet Architectures: An overview", *IETF RFC 1633*,1984.
- [7] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W.Weiss, "An Architecture for Differentiated Service", *IETF 2475*, 1998.
- [8] B. Kim, Y. Cho, J. Lee and D. Montgomery, "Performance of Optical Burst Switching Techniques in Multi-hop Networks", *IEEE GLOBECOM* 2002.
- [9] Y. Chen, M. Hamdi, and D.H.K. Tsang, "Proportional QoS over OBS networks", *IEEE GLOBECOM* 2001.

- [10] V. Vokkarane, Q. Zhang, J. Jue and B.Chen, “Generalized Burst Assembly and Scheduling Techniques for QoS Support in Optical Bursted-Swtiched Networks”, IEEE GLOBELCOM 2002.
- [11] R. Ramjee, D. Towsley, and R. Nagarajan, “ On Optimal Call Admission Control in Cellular Networks”, Wireless Networks 3 (1997) 29-41.
- [12] X. Yu, Y. Chen and C. Qiao, “Performance Evaluation of Optical Burst Switching with Assembled Burst Traffic Input”, IEEE GLOBECOM 2002.
- [13] Arthur. Y.-M. Lin, and John A. Silvester, “Priority Queueing Strategies and Buffer Allocation Protocols for Traffic Control at an ATM Integrated Broadband Switching System”, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS 1991.
- [14] L. Kleinrock, Queueing Systems, volume 1: Theory. A Wiley-Interscience Publication, 1975.
- [15] M. Yoo, C. Qiao and S. Dixit, “QoS Performance in IP over WDM Networks”, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS 2000.
- [16] L. Yang, Y. Jiang and S. Jiang, “A Probabilistic Preemptive Scheme for Providing Service Differentiation in OBS Networks”, IEEE GLOBECOM 2003.
- [17] C. Loi, W. Liao and D. Yang, “Service Differention in Optical Burst Switched Networks”, IEEE GLOBECOM 2002.

# Appendix A

## *Appendix A.1 Proof of Lemma 1 (Two-class VCR system).*

Let us first define a state  $(n_1, n_2)$  to be one where there are  $n_1$  class 1 and  $n_2$  class 2 reservations. Figure 14 shows the state transition diagram for VCR in a two-class system, in the form of a right-angle triangle. The threshold for class 1 is assumed to be  $k_1$ . At a state  $(n_1, n_2)$ , if  $n_1 + n_2 < T$  (i.e. there are still available channels), the incoming reservation request from either class will be granted. In Figure 14, all states, except those on the hypotenuse, fall into this category. Every state  $(n_1, n_2)$  on the hypotenuse satisfies the equation  $n_1 + n_2 = T$ , which means the system is fully reserved. In such situations, any incoming class 2 control headers will be dropped. An incoming class 1 control header, however, will be dropped only if the number of channels reserved by class 1 bursts has already reached or exceeded the threshold  $k_1$ , otherwise it will simply preempt a class 2 reservation.

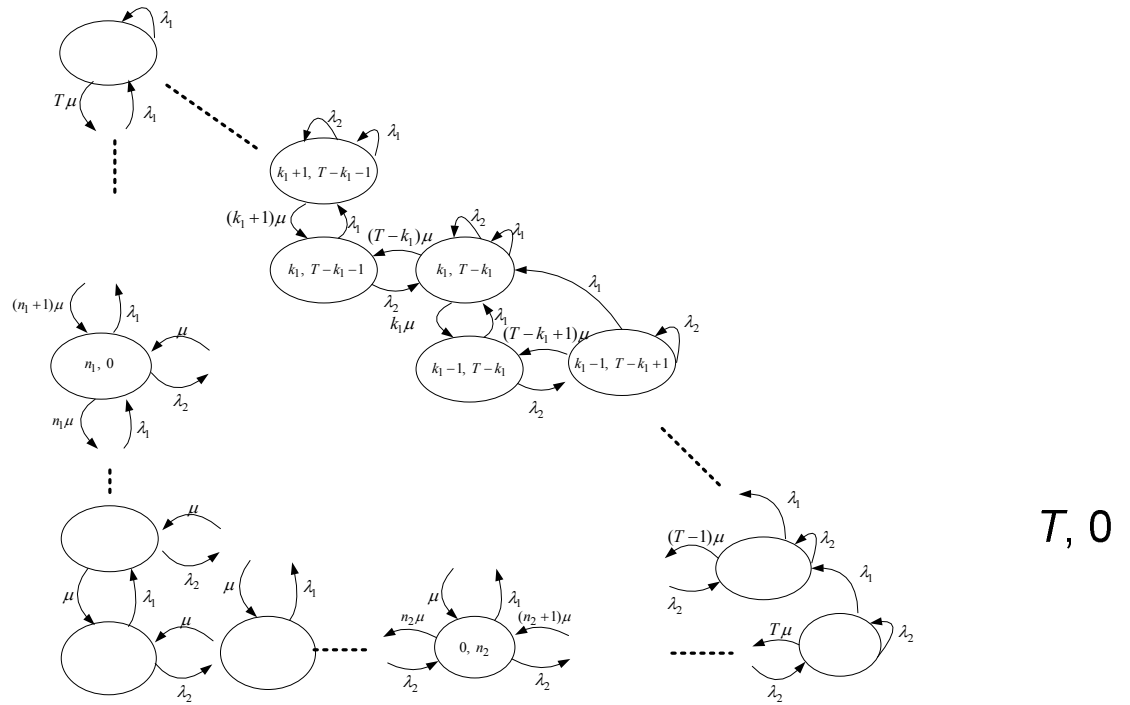


Figure a.1 States transition diagram for two-class VCR system

Through careful observation, we have classified the states in Figure a.1 to four groups. The transitions from the different groups of states to their neighbouring states are illustrated in Figure a.2. Based on such transitions, the general expression of balance equations for state  $(n_1, n_2)$  can be derived.



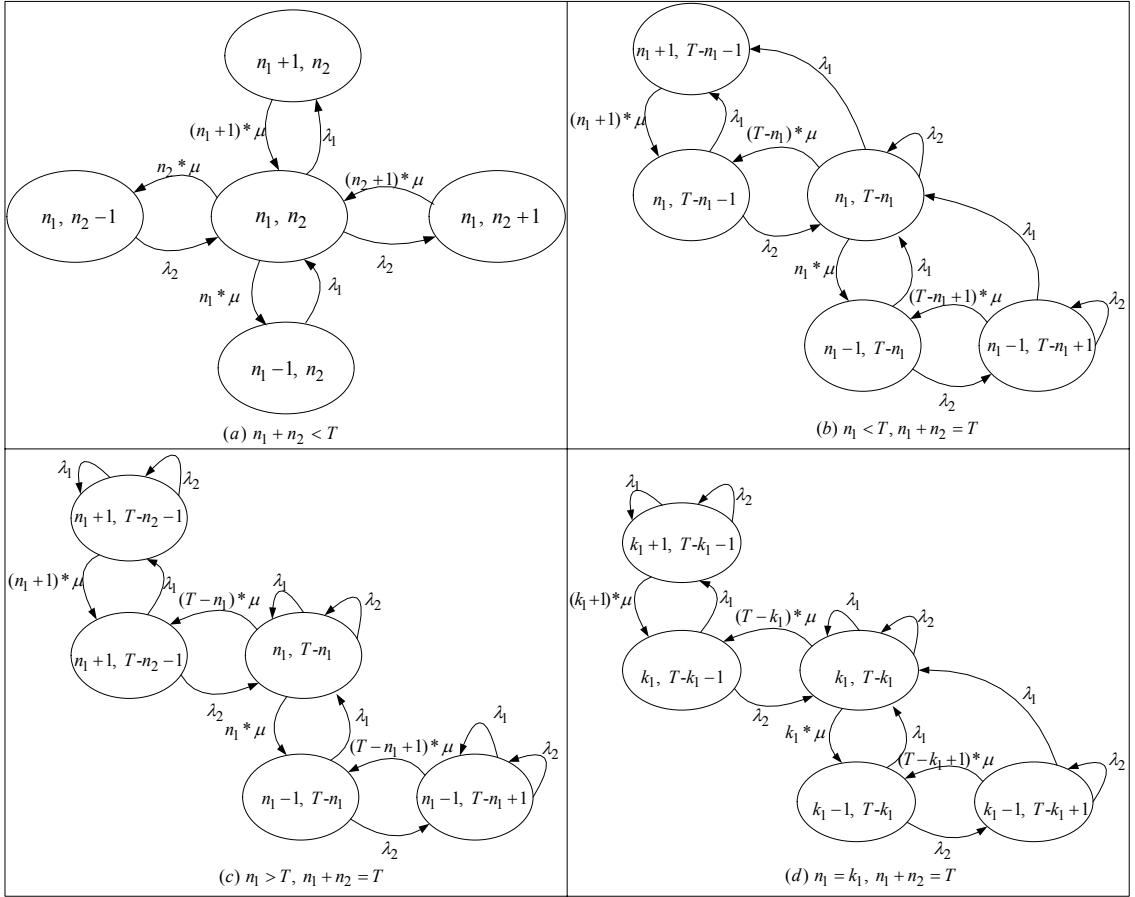


Figure a.2 States transition diagrams for state  $(n_1, n_2)$

If  $n_1 + n_2 < T$ ,

$$p(n_1, n_2) * (\lambda_1 + \lambda_2 + (n_1 + n_2)) = p(n_1 - 1, n_2) \lambda_1 + p(n_1, n_2 - 1) \lambda_2 + p(n_1 + 1, n_2) * (n_1 + 1) \mu + p(n_1, n_2 + 1) * (n_2 + 1) \mu$$

If  $n_1 < k_1, n_1 + n_2 = T$ ,

$$p(n_1, n_2) * (\lambda_1 + T \mu) = p(n_1 - 1, n_2 + 1) \lambda_1 + p(n_1 - 1, n_2) \lambda_1 + p(n_1, n_2 - 1) \lambda_2$$

If  $n_1 > k_1, n_1 + n_2 = T$ ,

$$p(n_1, n_2) * T \mu = p(n_1 - 1, n_2) \lambda_1 + p(n_1, n_2 - 1) \lambda_2$$

If  $n_1 = k_1, n_1 + n_2 = T$ ,

$$p(n_1, n_2) * T \mu = p(n_1 - 1, n_2 + 1) \lambda_1 + p(n_1 - 1, n_2) \lambda_1 + p(n_1, n_2 - 1) \lambda_2$$

In addition,

$$\sum_{\{(n_1, n_2) \mid n_1, n_2 = 0, n_1 + n_2 \leq T\}} p(n_1, n_2) = 1$$

The state probabilities  $p(n_1, n_2)$  can then be obtained by solving the above set of balance equations. The drop probabilities of the two priority classes can be calculated from the above set of balance equations, where  $P_1$  and  $P_2$  denote the class 1 and class 2 drop probabilities, respectively. The equations are compatible with the following behaviours defined by VCR:

The incoming class 1 burst is only dropped when all channels are occupied and the number of channels reserved by class 1 bursts equals to or surpasses the threshold  $k_1$ .

Whenever the channels are fully occupied, the incoming class 2 burst will be dropped; in addition, when the number of channels reserved by class 1 burst is less than the threshold  $k_1$ , a fraction  $\lambda_1 / \lambda_2$  of the scheduled class 2 bursts may be preempted by class 1 bursts.

$$P_1 = \sum_{\{(n_1, n_2) \mid n_1 + n_2 = T; n_1 \geq k_1\}} p(n_1, n_2)$$

$$P_2 = \sum_{\{(n_1, n_2) \mid n_1 + n_2 = T\}} p(n_1, n_2) + \frac{\lambda_1}{\lambda_2} \sum_{\{(n_1, n_2) \mid n_1 + n_2 = T; 0 \leq n_1 < k_1\}} p(n_1, n_2)$$

## Appendix A.2 Proof of Lemma 2 (Three-class VCR system)

Similar to the two-class systems, let's first define a state  $(n_1, n_2, n_3)$  to be one where there are  $n_1$  class 1,  $n_2$  class 2, and  $n_3$  class 3 reservations. While the state transition diagram for a two-class system is a two-dimensional right-angle triangle, the diagram of a three-class system is now a three-dimensional right-angle triangle, as shown in Figure b.1. Let us denote the threshold for class 1 and class 2 as  $k_1$  and  $k_2$ , respectively.

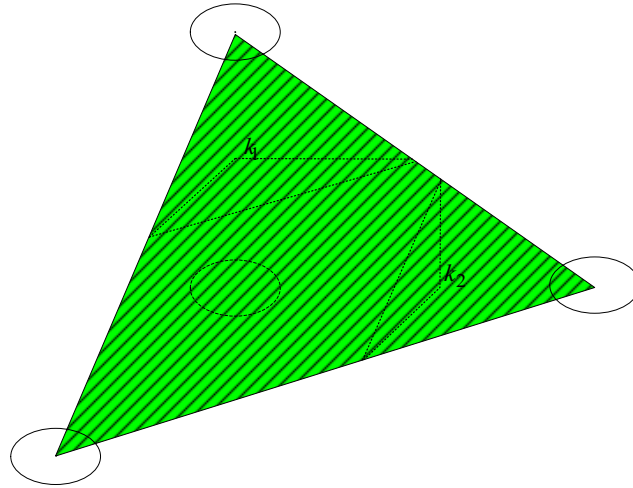


Figure b.1. State transition diagram for three-class VCR system

After applying analysis similar to that for a two-class system, we have found that at all states except those that fall on the surface  $ABC$ , the reservation request of any incoming burst, regardless of its class, will be granted. Their state balance equations follow the same general rule as listed in equation (11). After dividing all states on the surface  $ABC$  into fourteen cases, their state balance equations are listed below.

If  $n_1 + n_2 + n_3 < T$ ,

$$p(n_1, n_2, n_3) * (\lambda_1 + \lambda_2 + \lambda_3 + (n_1 + n_2 + n_3)\mu) = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 \\ + p(n_1 + 1, n_2, n_3)(n_1 + 1)\mu + p(n_1, n_2 + 1, n_3)(n_2 + 1)\mu + p(n_1, n_2, n_3 + 1)(n_3 + 1)\mu$$

If  $n_1 < k_1, n_2 < k_2, n_3 \neq 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3)(\lambda_1 + \lambda_2 + (n_1 + n_2 + n_3)\mu) = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 \\ + p(n_1 - 1, n_2 + 1, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3 + 1)\lambda_2$$

If  $n_1 < k_1, n_2 \leq k_2, n_3 = 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3) * (\lambda_1 + (n_1 + n_2 + n_3)\mu) = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 \\ + p(n_1 - 1, n_2, n_3 + 1)\lambda_1 + p(n_1 - 1, n_2 + 1, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3 + 1)\lambda_2$$

If  $n_1 < k_1, n_2 > k_2, n_3 = 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3) * (\lambda_1 + (n_1 + n_2 + n_3)\mu) = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 \\ + p(n_1 - 1, n_2, n_3 + 1)\lambda_1 + p(n_1 - 1, n_2 + 1, n_3)\lambda_1$$

If  $n_1 < k_1, n_2 > k_2, n_3 \neq 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3) * (\lambda_1 + (n_1 + n_2 + n_3)\mu) = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 + p(n_1 - 1, n_2, n_3 + 1)\lambda_4$$

If  $n_1 < k_1, n_2 = k_2, n_3 \neq 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3) * (\lambda_1 + (n_1 + n_2 + n_3)\mu) = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 + p(n_1 - 1, n_2, n_3 + 1)\lambda_4 \\ + p(n_1, n_2 - 1, n_3 + 1)\lambda_2$$

If  $n_1 > k_1, n_2 < k_2, n_3 \neq 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3) * (\lambda_2 + (n_1 + n_2 + n_3)\mu) = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 + p(n_1, n_2 - 1, n_3 + 1)\lambda_2$$

If  $n_1 > k_1, n_2 < k_2, n_3 = 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3) * (n_1 + n_2 + n_3)\mu = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 + p(n_1, n_2 - 1, n_3 + 1)\lambda_2$$

If  $n_1 > k_1, n_2 > k_2, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3) * (n_1 + n_2 + n_3)\mu = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3$$

If  $n_1 > k_1, n_2 = k_2, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3) * (n_1 + n_2 + n_3)\mu = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 + p(n_1, n_2 - 1, n_3 + 1)\lambda_2$$

If  $n_1 = k_1, n_2 < k_2, n_3 \neq 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3) * (\lambda_2 + (n_1 + n_2 + n_3)\mu) = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 \\ + p(n_1 - 1, n_2, n_3 + 1)\lambda_1 + p(n_1, n_2 - 1, n_3 + 1)\lambda_2$$

If  $n_1 = k_1, n_2 \leq k_2, n_3 = 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3)^*(n_1 + n_2 + n_3)\mu = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 + p(n_1 - 1, n_2, n_3 + 1)\lambda_4 \\ + p(n_1 - 1, n_2 + 1, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3 + 1)\lambda_2$$

If  $n_1 = k_1, n_2 > k_2, n_3 = 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3)^*(n_1 + n_2 + n_3)\mu = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 + p(n_1 - 1, n_2, n_3 + 1)\lambda_4 \\ + p(n_1 - 1, n_2 + 1, n_3)\lambda_1$$

If  $n_1 = k_1, n_2 > k_2, n_3 \neq 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3)^*(n_1 + n_2 + n_3)\mu = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 + p(n_1 - 1, n_2 + 1, n_3)\lambda_4$$

If  $n_1 = k_1, n_2 = k_2, n_3 \neq 0, n_1 + n_2 + n_3 = T,$

$$p(n_1, n_2, n_3)^*(n_1 + n_2 + n_3)\mu = p(n_1 - 1, n_2, n_3)\lambda_1 + p(n_1, n_2 - 1, n_3)\lambda_2 + p(n_1, n_2, n_3 - 1)\lambda_3 + p(n_1 - 1, n_2, n_3 + 1)\lambda_4 \\ + p(n_1, n_2 - 1, n_3 + 1)\lambda_2$$

In addition,

$$\sum_{\{(n_1, n_2, n_3) \mid n_1, n_2, n_3=0, n_1+n_2+n_3 \leq T\}}^T p(n_1, n_2, n_3) = 1$$

Using these equations, we can calculate the drop probability of the three classes. By calculating for all states at which a burst of a particular class is likely to be dropped or preempted, we can obtain the general form of drop probability for that particular class. The following are the respective equations:

### Class 1:

Since class 1 traffic has the highest priority, the only scenario where an incoming class 1 burst could be dropped is when the system is fully reserved, and the current number of reserved channels by class 1 bursts has reached or exceeded the class 1 threshold,  $k_1$ .

$$P_1 = \sum_{\{(n_1, n_2, n_3) \mid n_1 \geq k_1, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3)$$

### Class 2:

In a few scenarios a class 2 burst will be dropped or preempted:

- The system is fully reserved, and the number of channels currently reserved by class 2 bursts has reached or exceeded class 2 threshold  $k_2$ ;
- The system is fully reserved, and the number of channels reserved by class 3 bursts is zero. In this case, even the current class 2 bursts in the system is below its threshold, its control header will be rejected since there's simply no burst to preempt;
- The system is fully reserved, there is no channel reserved by a class 3 burst, and the number of channels reserved by class 1 bursts is below its threshold. In this case, an incoming class 1 control header will preempt a class 2 burst.

$$P_2 = \sum_{\{(n_1, n_2, n_3) \mid n_2 \geq k_2, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) + \sum_{\{(n_1, n_2, n_3) \mid n_2 < k_2, n_3 = 0, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) + \frac{\lambda_1}{\lambda_2} \sum_{\{(n_1, n_2, n_3) \mid n_1 < k_1, n_3 = 0, n_2 \neq 0, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3)$$

### Class 3:

A class 3 burst may be dropped or preempted in the following situations:

- The system is fully reserved;
- The system is fully reserved, an incoming class 1 control header may preempt a class 3 burst;
- The system is fully reserved, an incoming class 2 control header may preempt a class 3 burst.

$$\begin{aligned}
P_3 = & \sum_{\{(n_1, n_2, n_3) \mid n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) + \frac{\lambda_1}{\lambda_3} \sum_{\{(n_1, n_2, n_3) \mid n_1 < k_1, n_3 \neq 0, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3) \\
& + \frac{\lambda_2}{\lambda_3} \sum_{\{(n_1, n_2, n_3) \mid n_2 < k_2, n_3 \neq 0, n_1 + n_2 + n_3 = T\}} p(n_1, n_2, n_3)
\end{aligned}$$