PROVIDING SERVICE DIFFERENTIATION IN OBS NETWORKS THROUGH PROBABILISTIC PREEMPTION

YANG LIHONG
(*B.ENG(Hons.), NTU*)

A THESIS SUBMITTED
FOR THE DEGREE OF MASTER OF ENGINEERING
DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING
NATIONAL UNIVERSITY OF SINGAPORE
2003

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

______________________ ______________________

Date Yang Lihong

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Dr. Jiang Yuming. Thanks for giving me the advice on choosing a topic of my research. The project won't be a success without his kind support and insightful guidance.

Thank Dr. Jiang Shengming for giving me valuable comments on the paper and thesis writing. Thank all the lab technicians in the Institute for Infocomm Research, for their passionate help and technical support throughout the research.

Finally, I would like to acknowledge the Department of Electrical and Computer Engineering, NUS. Thanks for giving me an opportunity to pursue a graduate research.

Contents

Summary

While Internet traffic and on-line e-business are booming, how to support the rapidly growing bandwidth demand and different quality of service (QoS) requirements has become an important issue. To achieve this, Wavelength Division Multiplexing (WDM), which can offer enormous bandwidth, is deployed as a core transmission technology in the backbone network, and Optical Burst Switching (OBS) is proposed to support IP-over-WDM networks, which can provide all-optical, high-speed data rate, and format transparent switching. In this thesis, a novel scheme, called Probabilistic Preemptive scheme, is proposed and investigated for achieving service differentiation in such networks.

The main idea behind the Probabilistic Preemptive scheme is that a probabilistic parameter is added to the existing preemptive scheme. With this scheme, a high priority burst may preempt a low priority burst based on it probabilistic parameter to release the transmission period to the high priority burst. By changing the probabilistic parameter, the Probabilistic Preemptive scheme can achieve flexible blocking differentiation.

Various aspects of the proposed Probabilistic Preemptive scheme are studied in this thesis. First, for the two-class system, the impact of preemptive probability on blocking probabilities of the two classes and the blocking ratio of two classes are investigated through simulation. The overall performance of the two classes system in terms of overall blocking probability is analysed and simulated. By comparing with

the simulation results, it is shown that the proposed scheme conforms to the conservation law.

Second, for the multiple class system, the three classes system is studied as an example. The impact of preemptive probability on blocking probabilities of the three classes is studied through simulation. The overall performance of the three classes system in terms of overall blocking probability is simulated. By comparing with the simulation results, it is also shown that the proposed scheme conforms to the conservation law.

Third, for the multi-node system, the signalling issue is discussed. A release header is used to remove the switching information of the preempted burst in the downstream nodes of the network. The performance of a two-class system with or without releaser header are simulated and compared. It is shown in the simulation results that there is an improvement on the burst blocking probability for both high priority and low priority class. However, normally, the improvement on the high priority class is higher than that on the low priority class.

List of Figures

Chapter 1 Introduction to Optical Burst Switching

1.1 History of Optical Burst Switching (OBS)

While Internet and on-line e-business are booming, Internet traffic exponentially grows. Thus, the bandwidth demand is growing explosively. Wavelength Division Multiplexing (WDM) is deployed as a core transmission technology for the next generation backbone networks to support the increasing bandwidth requirement. WDM has a better employment of fibre capacity since it can support a number of high-speed (gigabit) wavelengths in a single fibre. Each fibre can carry bits at speed of the order of a gigabit per second. This provides enormous bandwidth at the physical layer.

In order to efficiently utilize this bandwidth, new protocols and management schemes are required. Researchers have proposed an IP over WDM network [1] as the core architecture for the next-generation optical Internet. This is because presently WDM is mainly deployed in the backbone of major long distance carriers as point-to-point links with a synchronous optical network (SONET) as a standard interface to higher layers in the protocol stack. This necessitates optic-electronic-optic (OEO) conversion at every node, and hence fails to take advantage of the wavelength routing capability provided by WDM technology. Also, electronic multiplexing layers – IP, asynchronous transfer mode (ATM) – introduce further bandwidth inefficiencies. Directly employing IP over WDM can avoid electronic bottleneck at OEO conversion and reduce complexities and overheads associated with the ATM and SONET layers as show in Figure 1-1. The WDM layer can provide the transmission of optical data which is transparent to bit rate and coding format.

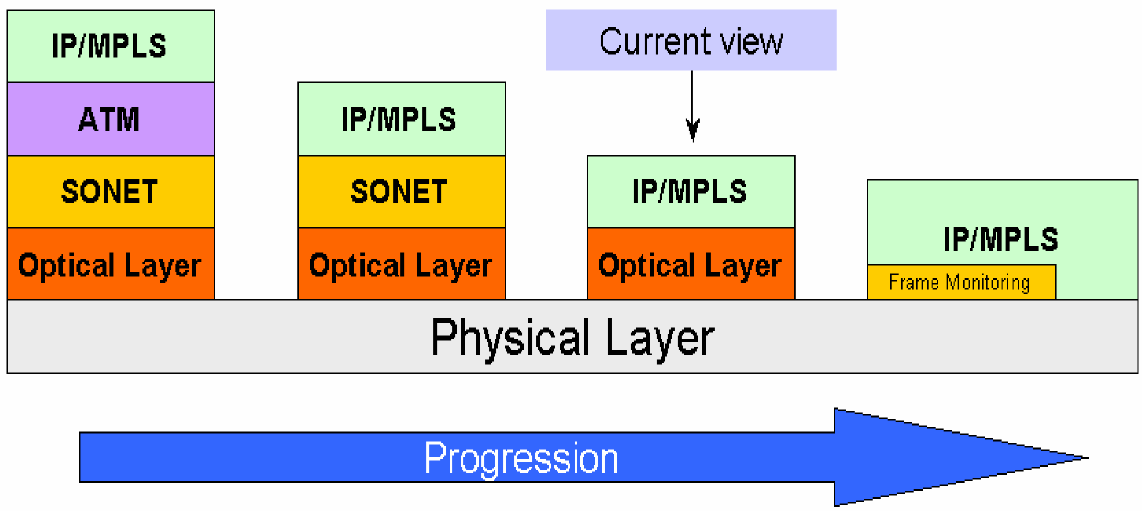


Figure 1-1: IP over WDM integration schemes

Basically, there are three switching paradigms for WDM networks: optical circuit switching (OCS), optical packet switching (OPS) and optical burst switching (OBS).

Optical circuit switching is the one that is deployed in the current WDM networks. Optical circuit switching uses wavelength routing to establish an all-optical wavelength path first. After that, data transmission cuts through the switching nodes. A round-trip delay is incurred in the connection set-up time since optical circuit switching requires a two-way reservation to set-up the lightpath. In addition, intermediate switches are all locked into the desired cross-connect states before the actual arrival of the data burst. Moreover, bandwidth reservation is necessary for the duration of the data transmission. The bandwidth cannot be shared by other transmissions. This leads to inefficient usage of cross-connect bandwidth. Optical circuit switching is advantageous when a constant data rate can be maintained on the network like voice traffic. However, it is not suitable for bursty traffic conditions, or when circuits are idle.

Optical packet switching is the long-term solution for the WDM networks. Optical packet switching does not need two-way reservation, and thus it has shorter set-up time. Unlike optical circuit switching, optical packet switching does not require the resource reservation, and thus the intermediate switches are open to any packet belonging to any source-destination pair. As a result, it has better utilization and good adaptation to the dynamics of higher layers. However, optical packet switching requires optical buffers at the intermediate nodes. Now optical buffers can only be realized using the Fibre Delay Lines (FDLs). If using the FDLs, there is a problem that the length of each packet cannot exceed the length of the available FDL in order for the optical packet to be buffered. Optical random access memory (RAM) is not available yet. Optical packet switching also requires stringent synchronization between control packet and payload.

Optical burst switching was introduced recently for optical (WDM) networks. Optical Burst Switching (OBS) [2][3] has been proposed as a promising solution to provide terabit optical routing and to build the all-optical WDM layer for the Optical Internet. Optical burst switching is designed to combine the advantages of optical circuit switching and optical packet switching while avoiding their main drawbacks. Optical burst switching avoids optical buffering while handling bursty traffic, and supports fast resource provisioning and asynchronous transmission of variable sized packets.

In optical burst switching, the basic switching entity is a burst, which contains a variable number of packets. The burst contains two components: control packet and data burst. Optical burst switching keeps data burst in the optical domain but separates control packet, which will do complex electronic processing. Optical burst switching uses out-of-band signalling – control packet and data burst are carried on different channels with a strong separation in time (offset time). A control packet is sent out ahead of its corresponding data burst to reserve wavelength along the path of the burst. The data burst consisting of multiple packets follows the header without waiting for an acknowledgement and passes through switching nodes optically without OEO conversion.

Optical Switching (Paradigm)	Bandwidth Utilization	Latency (set-up)	Optical Buffer	Proc. / Sync. Overhead (per unit data)	Adaptivity (traffic & fault)
Circuit	Low	High	Not required	Low	Low
Packet	High	Low	Required	High	High
Burst	High	Low	Not required	Low	High

Figure 1-2: Comparison of three paradigms

By choosing the offset time between the control packet and the data burst to be larger than the total processing time of control packet at the switching nodes along the path, one can eliminate the need for data burst to be buffered at intermediate nodes.

Compared with optical circuit switching, the pre-transmission latency of optical burst switching is lower. In addition, optical burst switching is much easier to be implemented in optical networks than optical packet switching because of less stringent requirement in synchronization and optical buffer. Figure 1-2 shows the comparisons of the three optical switching paradigms.

1.2 OBS Network Architecture

Figure 1-3 shows an optical burst switching network. It consists of the edge nodes and the core nodes. In the OBS network, optical burst switches are interconnected with WDM links.

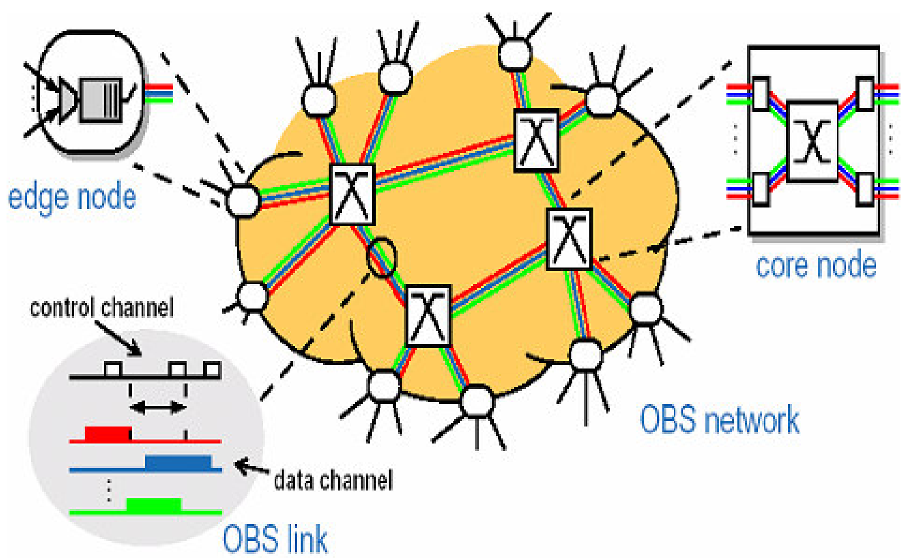


Figure 1-3: OBS Network Architecture

An optical burst switch transfers a burst coming in from an input port to its destination output port. Depending on the switch architecture, it may or may not be equipped with optical buffer. The fibre links carry multiple wavelengths, and each wavelength can be treated as a channel. The control packet associated with a burst will be transmitted on a separate control channel, which is not the same as the data channel. There can be many data channels. However, usually there is only one control channel. The burst is assembled at the ingress node by aggregating a number of IP packets destined to the same egress node.

An OBS switching node comprises of the following:

- *Input interface*: control packet and data burst reception and control packet conversion to electrical signal
- *Switching control unit*: header interpretation, scheduling, forwarding table lookup, switching matrix control, header rewriter and wavelength conversion control
- *Wavelength converters and optical delay lines*: the delay lines are used as a buffer to store the burst for a delay period
- *Optical switching unit*: space switches for switching the data burst from input port to output port

The edge nodes (ingress nodes or egress nodes) have additional functionality of burst creation by aggregation and de-aggregation. Different policies, such as having a threshold or a timeout, can be used to aggregate bursty data packets to create an optical burst and to send the burst into the network [4]. The core nodes have WDM receivers, WDM transmitters, WDM multiplexers, WDM demultiplexers, switch control units, wavelength converters, fibre delay lines and space division switches.

1.3 OBS Reservation Protocols

Optical burst switching techniques differ from each other based on how and when the network resources, such as bandwidth, are reserved and released.

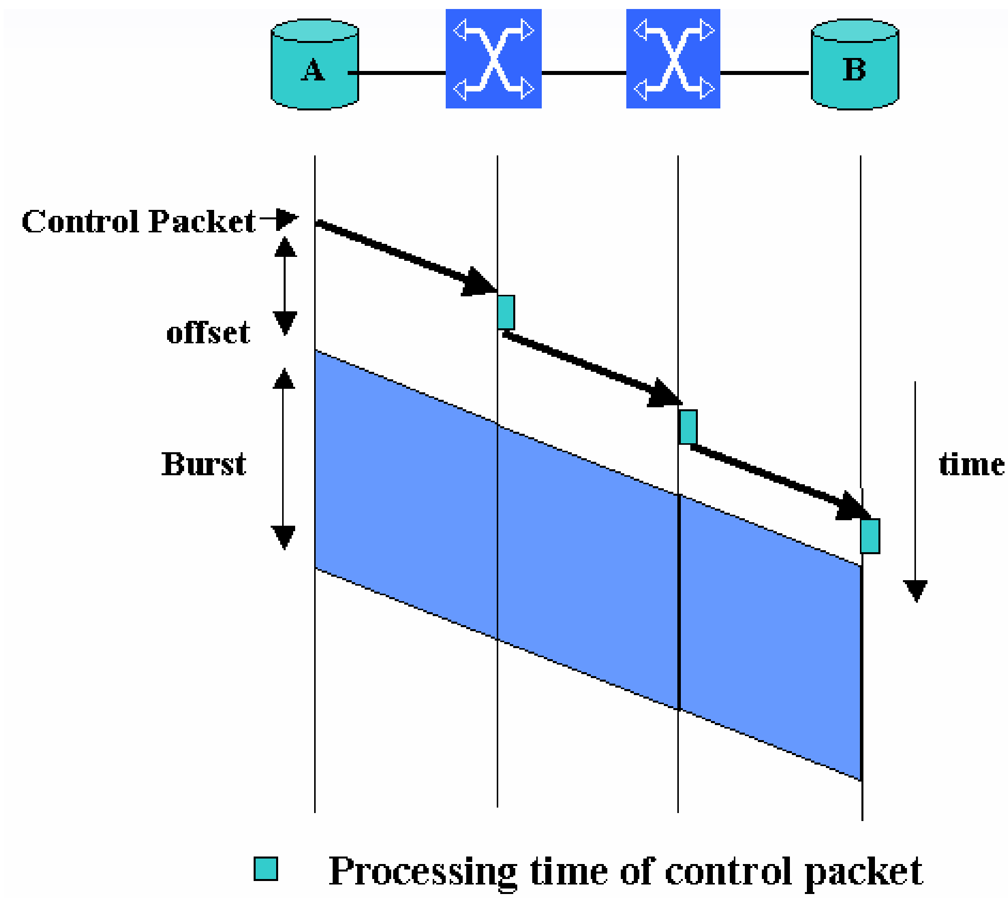


Figure 1-4: The use of offset time in OBS networks

In optical burst switched networks, the control packet and the data burst are separated at the source, as well as subsequent intermediate nodes, by an offset time, as shown in Figure 1-4. The offset time allows the control packet to be processed at each switching node while the burst is buffered electronically at the source node. Thus, no optical buffers are required at the intermediate nodes to delay the burst while the header is being processed. The control packet contains the information about the duration of the burst in order to let the switching node know when it may reconfigure its switch for the next burst.

In the tell-and-go (TAG) scheme [5][6], the source transmits the control packet and then immediately transmits the optical burst. In this scheme, it may be necessary to buffer the burst in the optical burst switch until its control packet has been processed. In the JET scheme [2], there is a delay between the transmission of the control packet and the transmission of the data burst. This delay can be set to be larger than the total processing time of the control packet along the path. With this way, when the data burst arrives at each intermediate node, the control packet has been processed and a channel, if available, on the output link has been allocated. Therefore, there is no need to buffer the burst at the switching node. This is a very important feature of the JET scheme, since optical buffers are difficult to implement.

A further improvement of the JET scheme can be obtained by reserving resources at the switching node from the time the burst arrives, rather than from the time its control packet is processed. In [7] a variation of JET was proposed to support quality of service. Specifically, two traffic classes were defined: real-time and none-real-time.

A burst belonging to the real-time class is allocated higher priority by simply using an additional offset time.

1.4 Research Objectives

The optical burst switching network architecture, its advantages, issues, reservation policies and related concepts have been discussed in this chapter. In the remaining, the focus is on service differentiation in OBS networks. In particular, a new scheme is introduced for providing service differentiation in OBS networks, which is called *Probabilistic Preemptive* Scheme. While simple, the proposed scheme is flexible and it can provide effective support of service differentiation in OBS networks. The proposed Probabilistic Preemptive scheme does not require any use of buffer at a switching node. Nor does it introduce additional delay. The proposed scheme provides another option for achieving service differentiation in an OBS network, which does not exclude the integration with other schemes with the same purpose. The details of the proposed scheme will be introduced in Chapter 3.

1.5 Organization of this Thesis

This thesis consists of five chapters. The first chapter has introduced optical burst switching, explained the motivation of carrying out this research and provided an overview of the work done. Chapter 2 provides the literature review of the research works and the techniques used in the field of service differentiation in OBS. Chapter 3 provides an overview of the proposed scheme and analyses it through multi-dimensional Markov chain. Explicit analytical results are given for a single-channel two-class system. Simulation results for two-class system are provided to validate analytical results and study its ability in providing service differentiation. The simulation results are provided to show the impact of various factors on the blocking probabilities, blocking ratio, system utilization and overall system performance. For the multiple class system, a three-class system is studied as an example. The simulation results are provided to show the impact of various factors on the blocking probabilities, system utilization and overall system performance. Chapter 4 addresses the signalling issue of Probabilistic Preemptive scheme in a multi-node system. The performances of the multi-node system with and without the release header are compared. Finally, Chapter 5 summarizes the work presented in this thesis and indicates some possible extensions to this work.

Chapter 2 Service Differentiation Schemes in OBS Networks

2.1 Overview

Current IP can only provide best effort service to deliver variable length packets. The future Internet demands differentiated services for multimedia applications, which require a high QoS (e.g. low delay and low loss probability). Thus, supporting QoS in optical burst switching networks is becoming an important issue. Particularly, in optical burst switching networks, how to support service differentiation at the WDM layer is a critical issue, since supporting basic service differentiation at WDM layer can facilitate as well as complement a QoS-enhanced version of IP. Among various QoS parameters, burst blocking probability is an important one when considering service differentiation in OBS networks [8]. This is because it is desirable to have low blocking probability for high priority traffic, even when the overall load is heavy and the number of available wavelengths is limited.

The IETF has proposed two frameworks in order to support QoS in IP networks: Integrated Services (IntServ) and Differentiated Services (DiffServ). IntServ requires a signaling mechanism, such as RSVP, to reserve network resources along the flow path. Applying IntServ, each packet must be processed by the router to determine its service class. In large IP networks, processing and policing individual packets impose a computation burden on the packet forwarding engine that limits the scalability of IntServ. DiffServ model was introduced to deal with the scalability issue in the

IntServ model. In DiffServ, scalability is achieved by aggregating packets with the same QoS requirement into fewer but coarser-grained flows. DiffServ flows are enforced locally on per-hop basis, simplifying the complexity of end-to-end QoS policing mechanism. In Diffserv, to achieve scalability packets are classified according to the code-point in the IP packet header.

Various service differentiation disciplines and scheduling algorithms have been proposed in the literature [9][10][11] for these two IETF frameworks. Most of them are based on packet switching, and mandate the use of buffers to isolate different classes of traffic. These schemes are called as the buffer-based schemes. These existing QoS schemes are not appropriate to be applied in an all-optical IP-over-WDM network because of the following two key reasons.

First, the use of electronic buffer would necessitate optic-electronic-optic (O/E/O) conversions at the intermediate nodes, which must be avoided in an all-optical IP-over-WDM network where data need to be kept in the optical domain at all intermediate nodes. Second, there is no optical random access memory (RAM) available yet. An optical data packet can only be delayed for a limited amount of time via the use of fibre-optical delay lines (FDLs). If using FDLs, there is a problem that the length of each packet cannot exceed that of the available FDL in order for the optical packet to be buffered. This calls for new QoS schemes that can take into account the unique properties of the WDM layer to enhance an all-optical OBS network to support service differentiation.

To enhance an all-optical OBS network to support service differentiation, a suitable QoS scheme needs to meet as many challenges as it can, which are stated as follows. First of all, the scheme should not degrade the overall performance of the system, especially in terms of burst blocking probability, i.e. the overall blocking probability of the whole system should not be increased after the QoS scheme is implemented. Second, the scheme needs to be simple to implement since the processing time is the main cause of delay in the WDM networks. Third, the scheme should avoid using optical buffer since optical buffer is not available yet. Fourth, the additional delay, if there is any, introduced by the QoS scheme should not be too large.

In the literature, several QoS schemes for optical burst switching networks can be found. The offset-time-based scheme [2] is the foremost one. Segmentation-based scheme [12] and intentional-dropping-based scheme [13] were proposed later. The advantages and disadvantages of these three schemes will be discussed in the following sub-sections.

2.2 Offset-time-based Scheme

In this scheme, the high priority class is given larger offset time. Having an extra offset time, the high priority class is able to reserve wavelength prior to the low priority class as shown in Figure 2-1. This scheme is suitable for implementation in bufferless WDM network since it does not mandate the use of any buffer as well as the complex queuing operations.

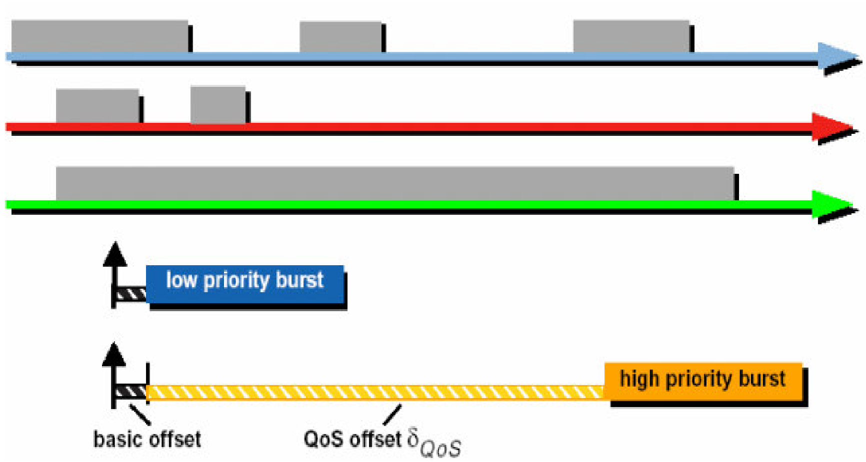


Figure 2-1: Offset-time-based scheme

Although this scheme can effectively achieve a good service differentiation by adjusting the extra offset time, it has some drawbacks. In [14], it is shown that to achieve the best differentiation, the extra offset time has to be at least 4 to 5 times larger than the basic offset time. This may affect the end-to-end delay much. Another problem with this scheme is that it has burst selecting effect, which is pointed out in [13]. The offset-time-based scheme is particularly unfair to long bursts of low priority since it tends to select the small bursts for low priority service classes. As the traffic intensity increases, the selection becomes stricter.

The third problem with this scheme is the so-called near-far problem in a multi-hop network. Since the offset time is set according to path length as well as priority, there is a situation where two control packets arrives at the same switch node and they contain the same offset time, which represent different meanings. One is low priority burst with a large number of hops to travel, while the other is the high priority burst with extra offset time. In this case, the switching node could treat them equally. In an even worse situation, a switching node may see larger offset time of a low priority burst than that of a high priority burst. Consequently, the low priority burst may have higher chance to get a channel than the high priority burst if the offset-time-based scheme is adopted.

2.3 Segmentation-based Scheme

In this scheme, a burst is divided into basic transport units called segments. Each segment has additional header information. Different priority segments are assembled into a burst at ingress node in the OBS network. In each burst, segments are placed from the head to the tail of the burst in the order of decreasing priority. When contention occurs, only those segments of a given burst, which overlaps with segments of another burst, will be dropped. That is, the tail of one burst, which is the segments containing lower priority packets, will be dropped or deflected whereas the remaining part of the burst can still be delivered to the destination node. Thus, less packets are lost compared to a solution of dropping a whole burst. However, this scheme encounters increased complexity for burst assembling at the source node and burst scheduling at the intermediate switching node as well as packets ordering at the destination node.

2.4 Intentional-dropping-based Scheme

This scheme requires a burst dropper at each switching node. The blocking rate of each traffic class is maintained in a pre-defined proportion. The service differentiation in terms of blocking probability is proportional to the factors that a network service provider sets. If q_i is the blocking probability and s_i is the differentiation factor for class i, using the proportional differentiation model, i.e., the equation as below:

$$\frac{q_i}{q_j} = \frac{s_i}{s_j} \qquad (i, j = 0, 1, \ldots\ldots\ldots N)$$

a low priority burst is dropped if the predefined blocking rate of its class is violated, regardless of whether there is an idle channel or not. Intentional dropping gives more or longer free periods of wavelengths and hence more opportunity for a high priority burst to be admitted. This scheme can provide a controllable QoS differentiation on blocking probability. However, the problem of this scheme is that it always causes excessive dropping, which results in high overall blocking probability of the whole system and lower system utilization compared to the previous two schemes.

2.5 Overview of Probabilistic Preemptive Scheme

As none of the existing QoS schemes discussed in previous subsections is able to meet all the four challenges introduced in Section 2.1 at the same time, a new scheme, called Probabilistic Preemptive scheme is proposed in this thesis to provide service differentiation in terms of burst blocking probability in OBS networks. This scheme is based on preemptive discipline. The difference is that a preemptive probability is added to the high priority class. Thus, high priority bursts can preempt low priority bursts in a probabilistic manner.

Chapter 3 The Probabilistic Preemptive Scheme

3.1 Overview

The main idea behind the Probabilistic Preemptive scheme is that a probabilistic parameter is included to the existing preemptive scheme. This is similar to what has been used in several previous works [15][16][17], where the Probabilistic Priority discipline is designed for achieving service differentiation in electronic packet switching networks by adding a probabilistic parameter to the existing priority discipline. Nevertheless, the Probabilistic Preemptive scheme is different from the Probabilistic Priority discipline because of the following two reasons. First, the Probabilistic Preemptive scheme has its root on preemption, which, however, is not allowed in the Probabilistic Priority discipline. Second, performance metrics for them are different. While the former focuses on burst blocking or blocking differentiation, the latter is targeted for packet delay differentiation.

The existing preemptive scheme allows all data into the network whenever resources are available, but interrupt and discontinue the flows of lower priority data if high priority data need resources but there is no room to accommodate them. This preemptive scheme is usually not adopted in electronic networks because it is too harsh an approach. However, in OBS network, preemptive scheme can be implemented since the data burst has not arrived at the switching node when preemption occurs. The limitation of the preemptive scheme is that it does not provide any means to adjust service differentiation provided.

By changing the probabilistic parameter, the Probabilistic Preemptive scheme can achieve flexible blocking differentiation in OBS networks. With this scheme, when high priority bursts need wavelengths at a switching node but there is no wavelength periods to accommodate them, wavelength reservation is re-examined. A high priority burst may preempt a low priority burst based on its probabilistic parameter to release the transmission period to the high priority burst.

It is worth highlighting here that such preemption happens when the corresponding control packet for the high priority burst arrives. Since a control packet is sent out always before its corresponding data burst, each switching node has time to rearrange wavelength reservation even though there is no buffer available. Also note that the preemption is applied to the reserved transmission period not the real burst. Since the transmission period was initially reserved for the low priority burst, when it actually arrives to the node, it is dropped or blocked.

Probabilistic Preemptive scheme operates as follows. Let there be I classes of bursts. Throughout the rest of the thesis, without loss of generality, it is assumed that these classes are numbered such that bursts with a smaller class number have a higher priority than bursts with a larger class number. Each class is assigned a parameter $0 \leq p_i \leq 1$, $i = 1, 2, \ldots, I$. With preemptive probability p_i, class i bursts can preempt lower priority classes bursts, i.e. class $i+1$, $i+2, \ldots, I$. In the situation when there are several bursts with different class number available to be preempted by class i burst, it will preempt the lowest priority class burst, i.e., the burst with the largest class number. If there are more than one burst with the lowest priority, it randomly preempt one.

The two-class system case is discussed first. In this case, bursts are classified into two classes, namely class 1 and class 2. Class 1 is assumed to have high priority over class 2. For the high priority class, it is assigned a preemptive probability, *p*, with which it can pre-empt low priority class, i.e. class 2.

A switching node keeps a linked list to track the wavelength reservation information. Upon the arrival of a high priority class control packet, the switching node searches for a free period first. If the switching node cannot find a free period for that burst, it preempts a low priority burst based on the preemptive probability *p* as shown in Figure 3-1. If the preemption cannot be performed, such as all corresponding periods have been reserved for high priority bursts, the new coming high priority burst is simply dropped or blocked.

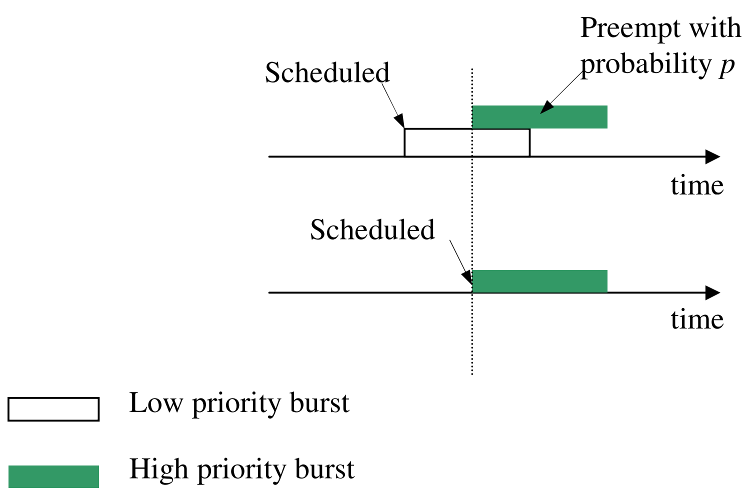
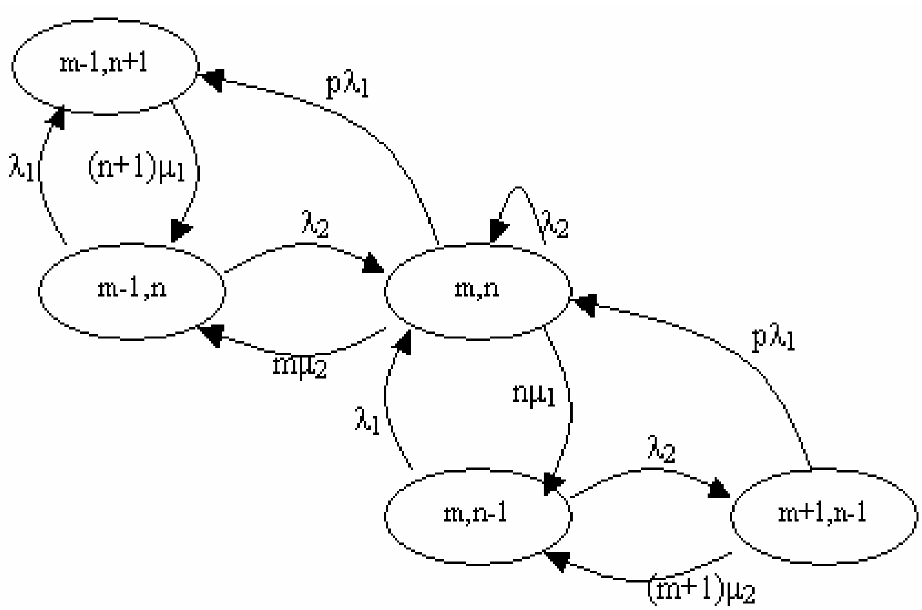


Figure 3-1: Probabilistic Preemptive Scheme

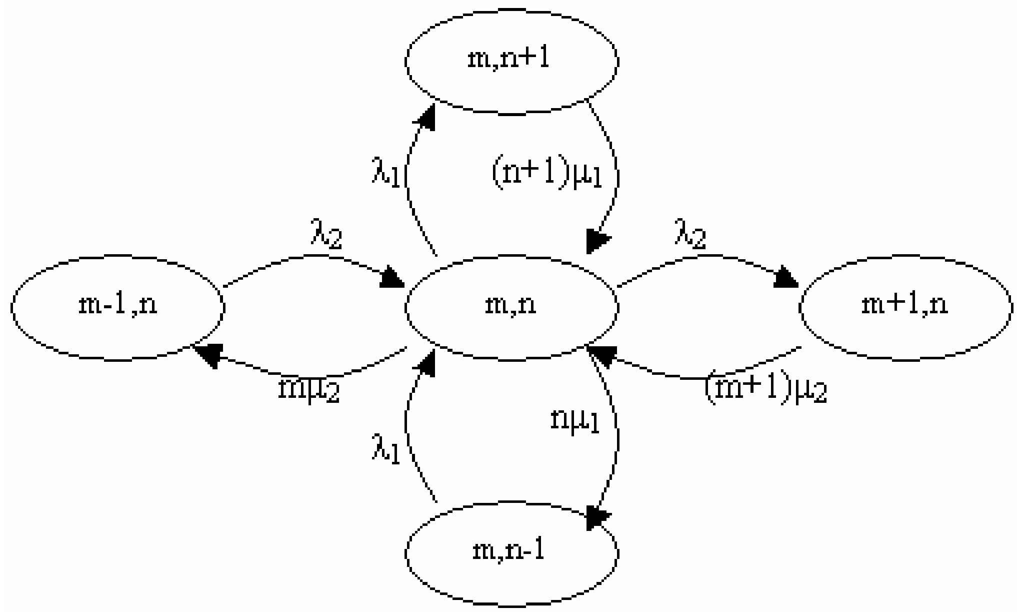
Clearly, the preemptive probability *p* affects the blocking probability for high priority class as well as for low priority class. High priority class can be assured to have lower blocking probability than low priority class, since we can allocate more resource to high priority class by increasing the preemptive probability *p*. Similarly, the preemptive probability p can be adjusted to get different blocking probability ratio between these two classes, i.e., the degree of blocking differentiation can be adjusted by changing preemptive probability p.

3.2 Analysis

In this section, the blocking probabilities of the two classes are analysed. The analysis is based on the following assumptions. First, bursts of class i arrive according to a Poisson process with the mean arrival rate λ_i. Note that such an assumption is adequate since it has been shown in [18][19] that Poisson arrival process can approximate real burst arrival after bursts assembly very well at the edge node. Second, service time of each class follows an exponential distribution with the mean service rate μ_i. Third, all classes of traffic share k wavelengths in the system and full wavelength conversion is assumed as for other schemes reviewed in the previous chapter.



(a) when $m+n=k$



(b) when $0 \leq m+n<k$

Figure 3-2: State transition diagrams for state (m,n)

Figure 3-2 shows the state transition diagrams for a typical state (m,n) in a two classes system, where the 2-tuple (m,n) represents a state in which m class 2 bursts and n class 1 bursts are in the system. Let $P_{m,n}$ be the probability that the system is in state (m,n). To get a general expression of balance equations, $P_{m,n}$ is simply set to be 0 if either $m<0$ or $n<0$. Then, based on Figure 3-2, the balance equations for state (m,n) can be written as follows:

If $0 \leq m+n <$k,

$$P_{m,n}(\lambda_1 + \lambda_2 + n\mu_1 + m\mu_2) - \lambda_1 P_{m,n-1} - \lambda_2 P_{m-1,n}$$

$$-(n+1)\mu_1 P_{m,n+1} - (m+1)\mu_2 P_{m+1,n} = 0 \qquad (1)$$

If $m+n=k$,

$$P_{m,n}(p\lambda_1 + n\mu_1 + m\mu_2) - \lambda_1 P_{m,n-1} - \lambda_2 P_{m-1,n}$$

$$- p\lambda_1 P_{m+1,n-1} = 0 \qquad (2)$$

In addition, we have

$$\sum_{\substack{m,n=0 \\ m+n \le k}}^{k} P_{m,n} = 1 \qquad (3)$$

To get the blocking probabilities of the two classes, the state probabilities $P_{m,n}$ is derived by solving above equations first. Then, the blocking probabilities of each priority class as well as the overall blocking probability can be obtained through proper equations. In the following subsection, we will show how these can be done for a single channel system as an example.

3.2.1 The Single Channel System

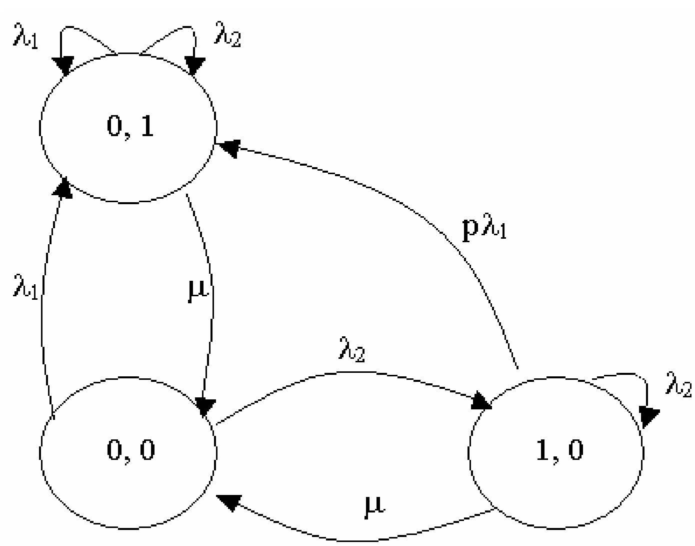


Figure 3-3: State transition diagram of a single-channel system

with probabilistic preemption

The above graph Figure 3-3 shows the state transition diagram for a single channel system, where it is assumed that the two classes have the same service rate μ. The balance equations for the single channel system are re-written as follows based on equations (1) and (2):

$$\lambda_1 P_{00} + p\lambda_1 P_{10} = \mu P_{01} \qquad (4)$$

$$\lambda_2 P_{00} = \mu P_{10} + p\lambda_1 P_{10} \qquad (5)$$

Together with

$$P_{00} + P_{10} + P_{01} = 1 \qquad (6)$$

The state probabilities can be obtained as:

$$P_{00} = \frac{\mu}{\lambda_1 + \lambda_2 + \mu}$$

$$P_{10} = \frac{\lambda_2 \mu}{(\mu + p\lambda_1)(\lambda_1 + \lambda_2 + \mu)}$$

$$P_{01} = \frac{\lambda_1 (p\lambda_1 + p\lambda_2 + \mu)}{(\mu + p\lambda_1)(\lambda_1 + \lambda_2 + \mu)}$$

Finally, the blocking probabilities p_i are calculated as:

1) For high priority class,

$$p_1 = P_{01} + (1 - p)P_{10}$$

which, clearly, comprises two parts:

- The probability that a high priority burst arrives at the state (0,1) and it is blocked.

- The probability that a high priority burst arrives at the state (1, 0). However, the preemption cannot be performed due to probability (1-p) and hence the burst is blocked.

2) For low priority class,

$$p_2 = (P_{01} + P_{10}) + \frac{\lambda_1}{\lambda_2} pP_{10}$$

This result is derived based on the following. Let us consider a large time interval T. In this interval, there are $(\lambda_1+\lambda_2)T$ arrivals. For these arrivals, there are totally $(\lambda_1+\lambda_2)TP_{00}$ transmitted successfully. Among those successfully transmitted bursts, $\lambda_1 T(1 - p_1)$ are high priority class 1 bursts and the remaining are low priority bursts. Hence, the blocking probability of low priority bursts in this interval is given by

$$1 - \frac{(\lambda_1 + \lambda_2)TP_{00} - \lambda_1 T(1 - p_1)}{\lambda_2 T}$$

By applying equation (6) in the above form, the blocking probability of the low priority class is obtained. Intuitively, this probability can also be considered as consisting of two parts:

- The probability that a low priority burst arrives at either state (0,1) or state (1,0) and is dropped.
- The probability p that low priority bursts at the state (1,0) are preempted by some high priority bursts. Here, there is a factor λ_1/λ_2 being enforced. It is to account that only this portion of class 2 bursts at the state (1,0) can be possibly preempted by high priority bursts due to the arrival rate difference between the two classes.

3) The overall blocking probability is calculated as:

$$p_{overall} = \frac{\lambda_2 p_2 + \lambda_1 p_1}{\lambda_1 + \lambda_2} = \frac{\lambda_1 + \lambda_2}{\lambda_1 + \lambda_2 + \mu}$$

For the overall blocking probability, it is interesting to notice that it has no relationship with the probability parameter p and hence it will not change even when p varies. This clearly shows that our scheme has the conformance to the conservation law in a single channel system. The conservation law will be discussed later in Section 3.2.3.

3.2.2 Achievable Blocking Differentiation

1) When $p = 1$:

Based on the analysis in the previous subsection, it is easy to verify that, for the Probabilistic Preemptive scheme, the lowest p_1 occurs when the preemptive probability p is equal to one. This means high priority bursts always preempt low priority bursts whenever it is necessary to do so. In addition, this lowest p_1 can be calculated using Erlang loss formula as follows:

$$p_1 = \frac{(\lambda_1 / \mu)^k / k!}{\sum_{n=0}^{k} (\lambda_1 / \mu)^n / n!} \tag{7}$$

which is also the lowest blocking probability for high priority class that any other scheme can achieve. This implies that the proposed scheme has the ability to achieve the largest burst blocking differentiation.

2) When $p = 0$:

For the worst case, high priority class bursts are not allowed to preempt any low priority class bursts, i.e. there is no differentiation between the two classes. This can also be achieved by the proposed scheme when the preemptive probability p is set to be 0. For this case, the two classes will have the same blocking probability, which can be calculated as below:

$$p_1 = p_2 = \frac{((\lambda_1 + \lambda_2)/\mu)^k / k!}{\sum_{n=0}^{k} ((\lambda_1 + \lambda_2)/\mu)^n / n!} \qquad (8)$$

Thus, for the high priority class, its burst blocking probability is bounded between equation (7) and equation (8). By adjusting the preemptive probability p, a desired blocking probability for the high priority class can be obtained between these two bounds.

3.2.3 Conformance to the Conservation Law

The conservation law [20] states that the sum of the blocking probabilities p_i encountered by a set of traffic classes, weighted by their shares of arrival rate λ_i, is independent of the scheduling discipline. In other words, $\Sigma(\lambda_i * p_i) = (\Sigma\lambda_i)*p_{overall}$, where $p_{overall}$ is the overall blocking probability of the system and is independent of the adopted scheduling scheme.

In [21], it has been conjectured that the conservation law holds for the extra offset-time-based scheme. The work in [21] verified through simulation that the overall performance, which is the overall burst blocking probability, of an extra offset-time based system stays the same regardless of the number of classes and the setting of extra delay to the offset-time.

For the Probabilistic Preemptive scheme, we also have the same conservation conjecture. The overall blocking probability of a Probabilistic Preemptive system stays the same regardless of the degree of service differentiation, i.e. the burst blocking ratio, which is determined by the preemptive probability *p*. From the analysis of the single channel case, it can be easily verified that this conjecture holds. For multiple-channel cases, such a conjecture will be verified through simulations in the next section.

3.3 Simulation results for the two-class system

In this section, whether the proposed Probabilistic Preemptive scheme can support service differentiation in OBS networks is tested by simulation results. Here, a single switching node system without buffer is used for simulation. It is assumed that the switching node has full wavelength conversion capability. In addition, there are 8 wavelengths or channels in its output link to transmit data bursts and 1 channel to transmit control packets. It is also assumed that there is no loss of control packets. The bursts of either class i arrive according to a Poisson process with the mean arrival rate λ_i. The burst service time of each class follows an exponential distribution with the same mean service rate. In the simulation, the same unit service rate μ is applied for the two classes, while the arrival rate of class 2 is twice of that of class 1, i.e., $\lambda_2 = 2\lambda_1$. In this project, a self-written simulator is used as the simulation tool. All the results presented were averaged over 20 simulation runs.

3.3.1 Impact of *p* on Burst Blocking Ratio

Figure 3-4 shows the burst blocking probability ratio between the two classes against the preemptive probability *p*. The blocking ratio refers to the blocking probability of high priority class 1 divided by that of low priority class 2. In this figure, the high and low priority class loads are 0.2 and 0.4 respectively.

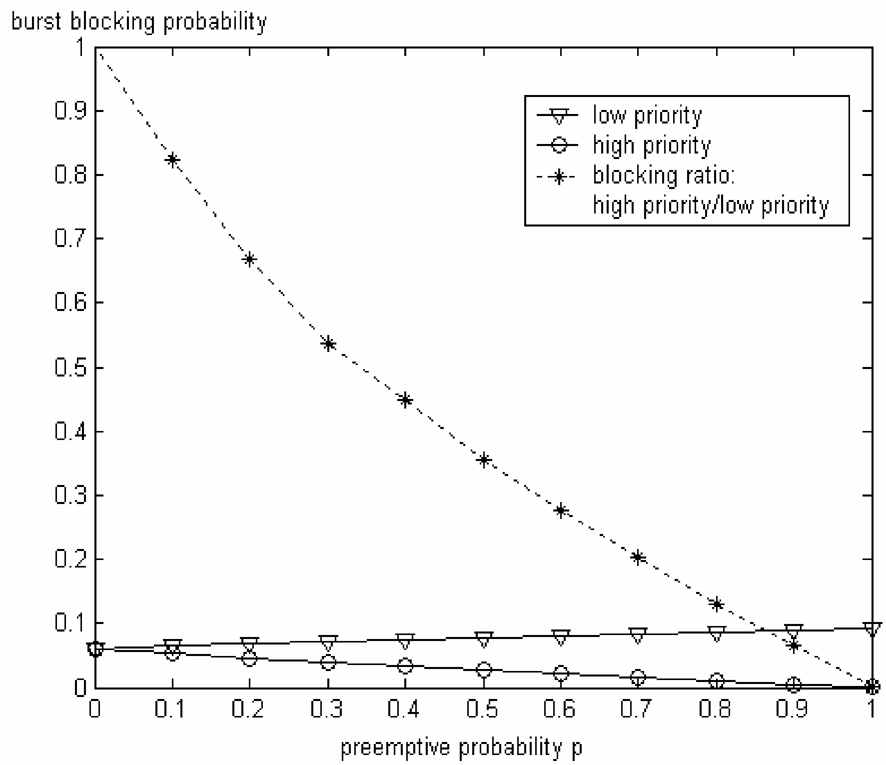


Figure 3-4: Preemptive probability *p* vs. blocking ratio

Figure 3-4 shows that the blocking probability ratio decreases when *p* increases. The blocking ratio equals to 1 when *p* is set to 0. This is the situation where preemption does not take place and the two classes have the same blocking probability. The maximum service differentiation occurs when *p* is set to 1, i.e., when the blocking ratio achieves the lowest value. At this situation, preemption will always be preformed whenever it is necessary. In addition, the desired blocking ratio can be obtained by adjusting *p*. This means any required service differentiation can be got between the results of these two extreme cases.

3.3.2 Impact of *p* on Blocking Probabilities

Figure 3-5 shows the blocking probabilities of the two priority classes against *p* for the 8-channel system.

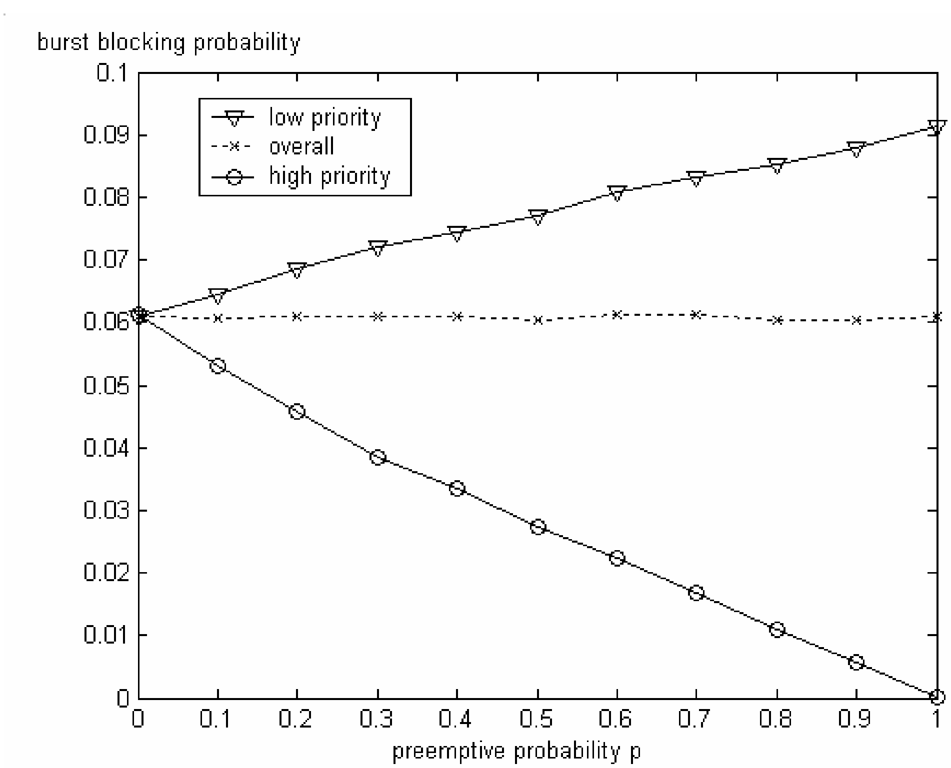


Figure 3-5: Preemptive probability *p* vs. blocking probabilities

Here again, the load of high priority class is 0.2 and the load of low priority class is 0.4. It can be seen from Figure 3-5 that the overall blocking probability stays the same regardless of the change of preemptive probability *p*. Hence, the Probabilistic Preemptive scheme can effectively achieve service differentiation, and at the same time it can maintain the overall performance in terms of overall burst blocking probability in the system. This also implies that the conjectured conservation law holds for the 8-channels system.

Figure 3-6 further shows the overall burst blocking probability against preemptive probability *p* for systems with some other number of channels with the same load condition.

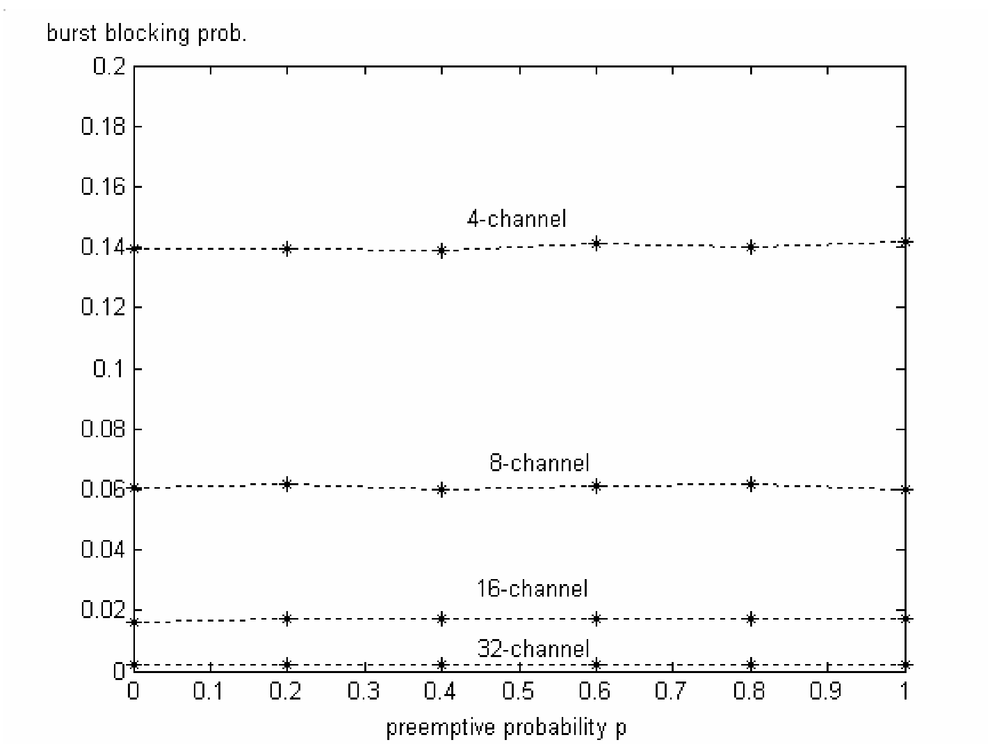


Figure 3-6: Preemptive probability *p* vs. overall blocking probability

Figure 3-6 illustrates the same phenomenon as shown in Figure 3-5 in terms of the overall burst blocking probability against preemptive probability *p*. These simulation results validate the conformance of the Probabilistic Preemptive scheme to the conservation law, which is discussed in Section 3.2.3, for all systems simulated.

3.3.3 Impact of Load on Burst Blocking Ratio

Figure 3-7 shows the impact of load as well as the preemptive probability *p* on burst blocking ratio between the two classes in the simulated system. Here, the blocking ratio again refers to the blocking probability of high priority class 1 divided by that of low priority class 2.

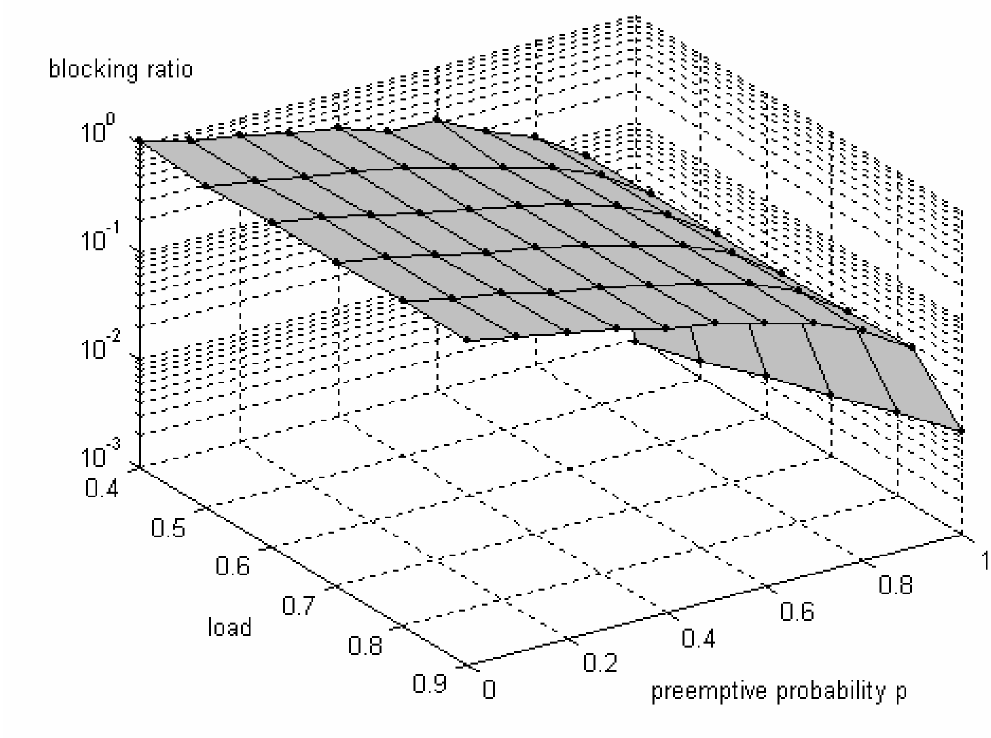


Figure 3-7: Blocking ratio vs. both load and preemptive probability *p*

It can be observed from the figure that, as load increases, the blocking ratio decreases. In addition, as *p* increases, the blocking ratio decreases due to more preemptions taking place. It is interesting to see that a desired blocking ratio can be maintained by adjusting *p* properly even when load condition changes. Clearly, the proposed Probabilistic Preemptive scheme is flexible for providing service differentiation in OBS networks.

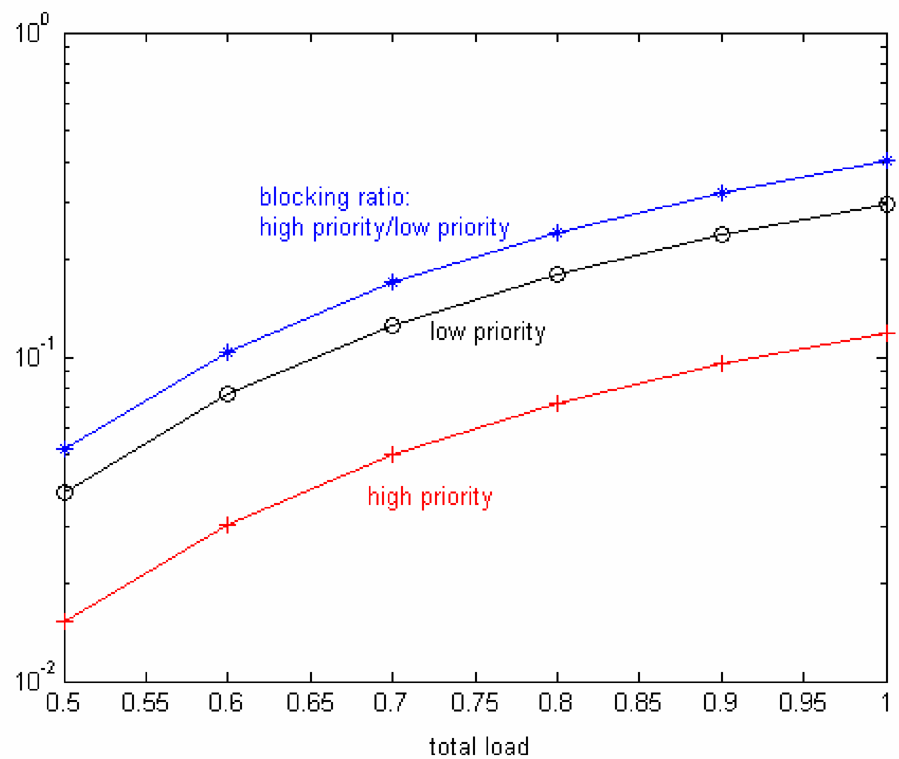


Figure 3-8: blocking ratio vs. load

Figure 3-8 shows the impact of changing load on the blocking ratio when p is fixed. This figure gives the blocking probabilities of high priority and low priority as well as the blocking ratio between them. For the simulation using in the Figure 3-8, *p* is set to be 0.5.

3.3.4 System Utilization and Transmission Effectiveness

Here let us define the transmission effectiveness as the percentage of the total transmission time of bursts successfully passing through the switching node over that of all bursts arriving at the switching node. That is also the total length of bursts successfully passing through over that of all bursts arriving at the switching node.

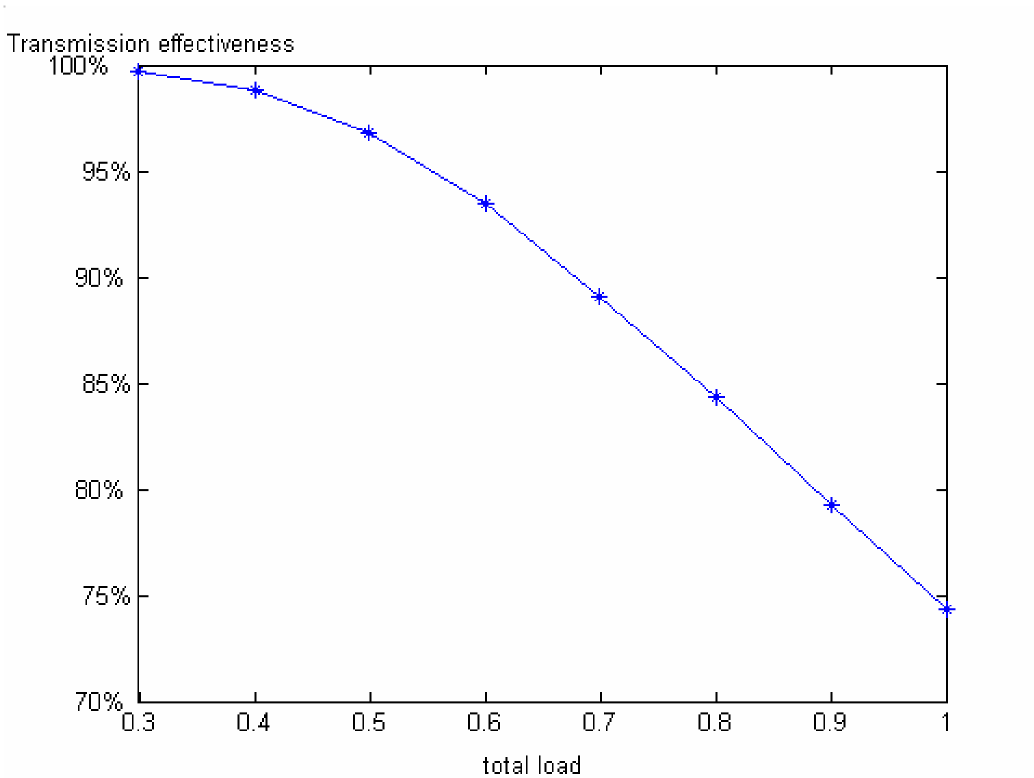


Figure3-9: Transmission effectiveness vs. total load

Figure 3-9 shows the transmission effectiveness vs. overall offered load changes when the preemptive probability *p* is set to be 0.8. We can see from the figure that the transmission effectiveness drops when the total offered load increases. When the load is 0.3, the transmission effectiveness almost reaches 100%. This is because at the light load condition, the blocking probabilities of both classes are very small. However, when the load is 1, the transmission effectiveness decreases to 75%. This is caused by more blocking of low priority class bursts when the load is increased. When the preemption takes place, the low priority burst with a longer packet length may have to be dropped. This results in a drop in the transmission effectiveness. However, even at this worst case, our probabilistic preemptive scheme still can achieve about 75% transmission effectiveness.

System utilization is defined as the percentage of the total transmission time of bursts successfully passing through the switching node over the total simulation time multiplied by the number of wavelengths.

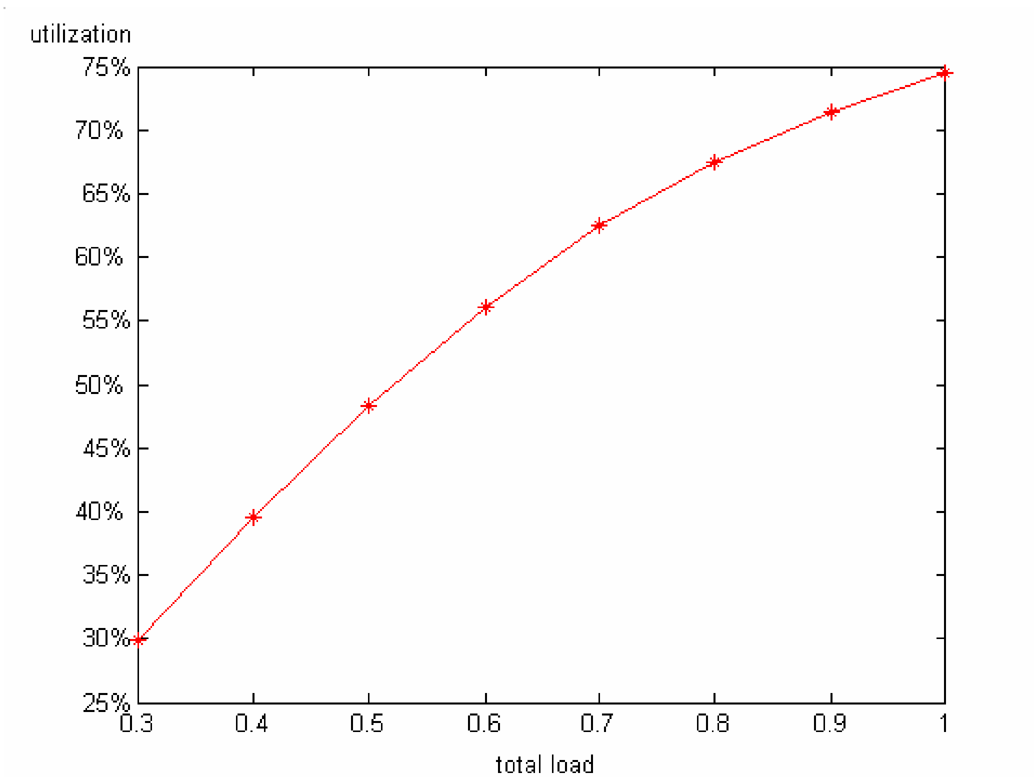


Figure 3-10: system utilization vs. total load

Figure 3-10 shows the system utilization vs. the total offered load when the preemptive probability *p* is set to be 0.8. The figure shows that the system utilization increases when the total offered load increases. That is what we expect. When the load is 0.3, the system utilization is just 30%. This is because at the light load condition, the wavelength resource is not fully utilized. When the load is 1, the system utilization increases to 75%. This is caused by more bursts are transmitted on the wavelengths. The system is much more utilized.

Figure 3-11 shows the transmission effectiveness and system utilization vs. preemptive probability *p* when the total offered load is set to be 0.9. It is shown in the figure that when the preemptive probability *p* increases from 0 to 1, both transmission effectiveness and system utilization slightly decrease. This is because when more preemtions take place, more low priority bursts are dropped.

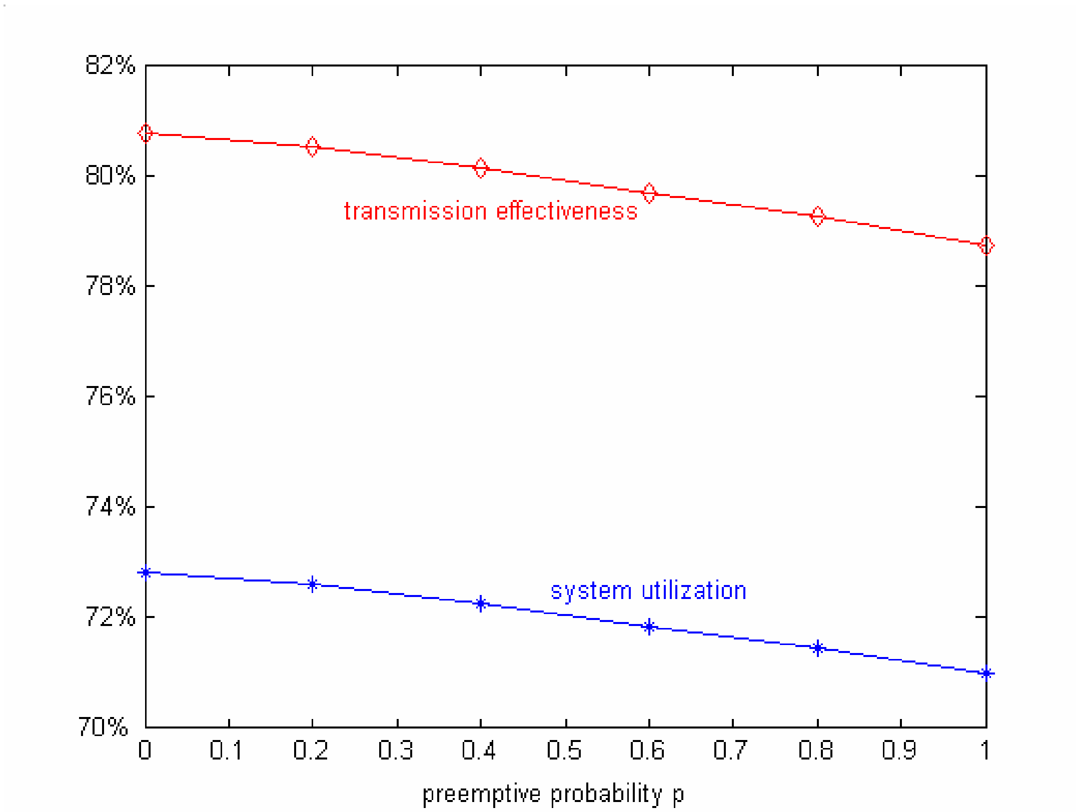


Figure 3-11: transmission effectiveness and system utilization vs. *p*

From the Figures 3-9, 3-10 and 3-11, it can be observed that the change of total offered load has large impact on both the transmission effectiveness and the system utilization when the preemptive probability p is fixed. However, if the total offered load is fixed, the preemptive probability p just has a small impact on the transmission effectiveness and the system utilization.

3.4 Simulation results for multiple class system

In this section, simulation results are presented to show that the proposed Probabilistic Preemptive scheme can be extended to support service differentiation in OBS networks multiple classes. For ease of exposition, three classes are considered, i.e., class 1, class 2 and class 3, with descending priorities. For class 1 and class 2, they are assigned a preemptive probability, p_1 and p_2 respectively. With preemptive probability p_1, class 1 can preempt low priority class, i.e. class 2 and class 3. In the situation when there is both class 2 burst and class 3 burst is possible to be preempted by class 1 burst, it will preempt the class 3 burst. Class 2 can preempt the lowest priority class, i.e., class 3, with preemptive probability p_2. Here again, a single switching node system without buffer is used for simulation. It is assumed that the switching node has full wavelength conversion capability.

In addition, there are 8 wavelengths or channels in its output link to transmit data bursts and 1 channel to transmit control packets. It is also assumed that there is no loss of control packets. The bursts arrive according to a Poisson process with the mean arrival rate λ_i. The service time of each class follows an exponential distribution with the same mean unit service rate μ. The arrival rates of the three classes are λ_1, λ_2 and λ_3 respectively. We set $\lambda_3 = \lambda_2 = \lambda_1$ and $p_1 = p_2 = p$.

3.4.1 Impact of *p* on the Blocking Probabilities

Figure 3-12 shows the blocking probabilities of the three priority classes against preemptive probability p (= p_1 = p_2) for the 8-channels system. Here, the load of each class is 0.3. The total offered load of the system is 0.9.

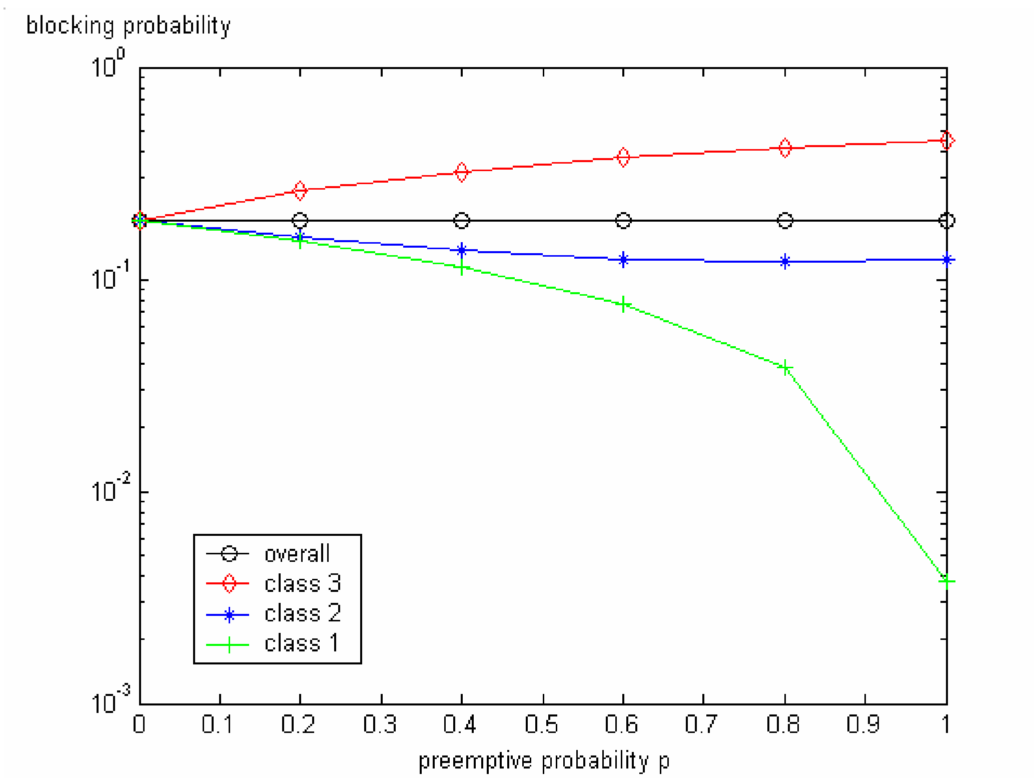


Figure 3-12: Preemptive probability p vs. blocking probabilities

It can be seen from Figure 3-12 that the overall blocking probability stays the same regardless of the change of preemptive probability p. Hence, the Probabilistic

Preemptive scheme can effectively achieve service differentiation, and at the same time maintain the overall performance in terms of overall burst blocking probability in the three-class system. This also implies that the conjectured conservation law holds for the 8-channel multiple class system.

Figure 3-13 further shows the overall burst blocking probability against preemptive probability p (= p_1 = p_2) for systems with some other number of channels with the same load condition in a three-class system.

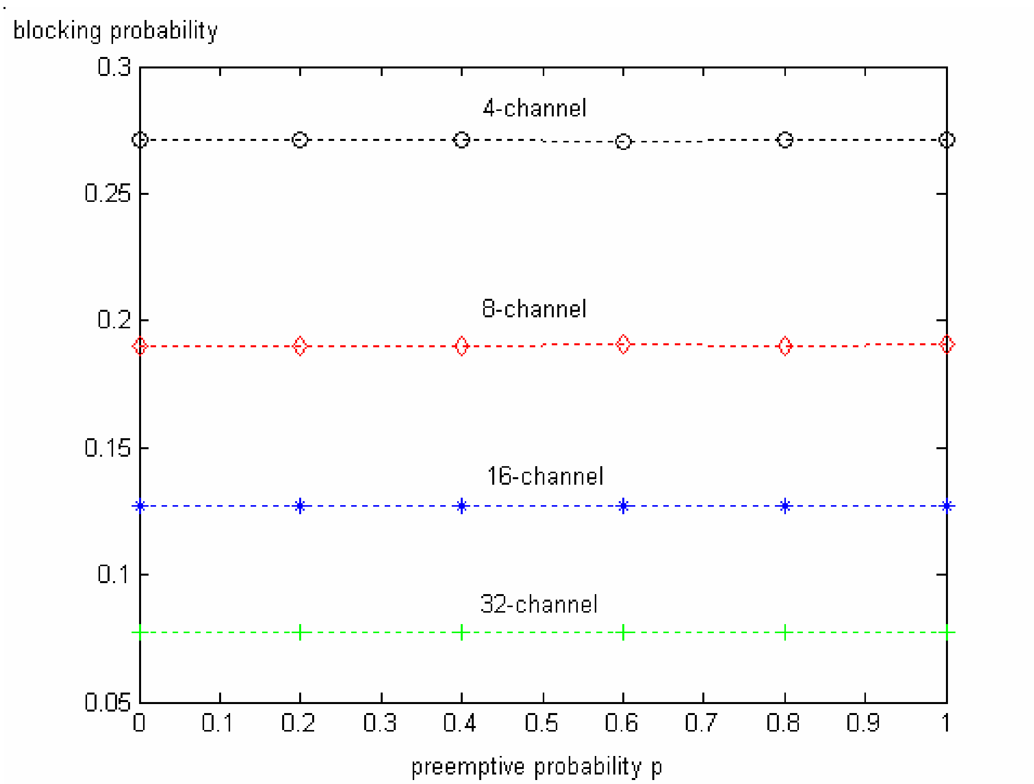


Figure 3-13: Preemptive probability p vs. overall blocking probability

Figure 3-13 illustrates the same phenomenon as shown in Figure 3-12 in terms of the overall burst blocking probability against preemptive probability p. These simulation results validate the conformance of the Probabilistic Preemptive scheme to the conservation law in a multiple class system, which is discussed in Section 3.2.3, for all the systems simulated.

3.4.2 Impact of load on blocking probabilities

Figure 3-14 shows that impact of load on the blocking probabilities of the three classes when the preemptive probability p (= p_1 = p_2) is set to be 0.8. Figure 3-15 shows that impact of load on the blocking probabilities of the three classes when p_1 is set to be 0.7 and p_2 is set to be 0.3. For both simulations, the total offered load of the system is fixed to 0.9.

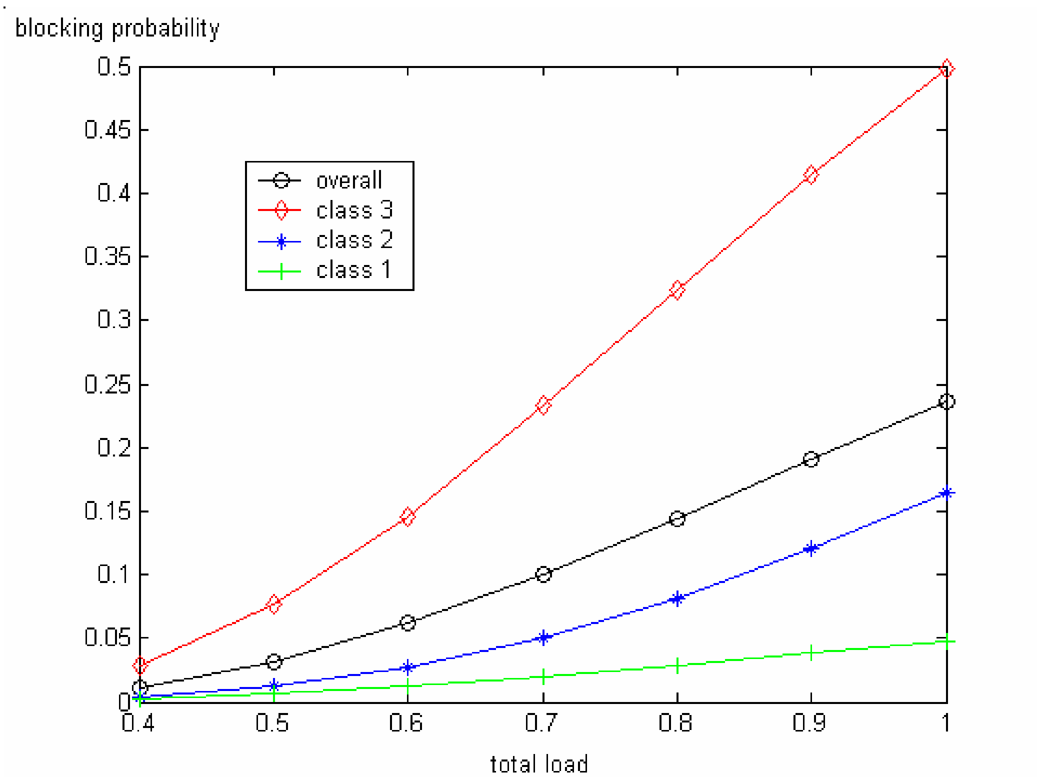


Figure 3-14: total load vs. blocking probabilities with p_1 = p_2 = 0.8

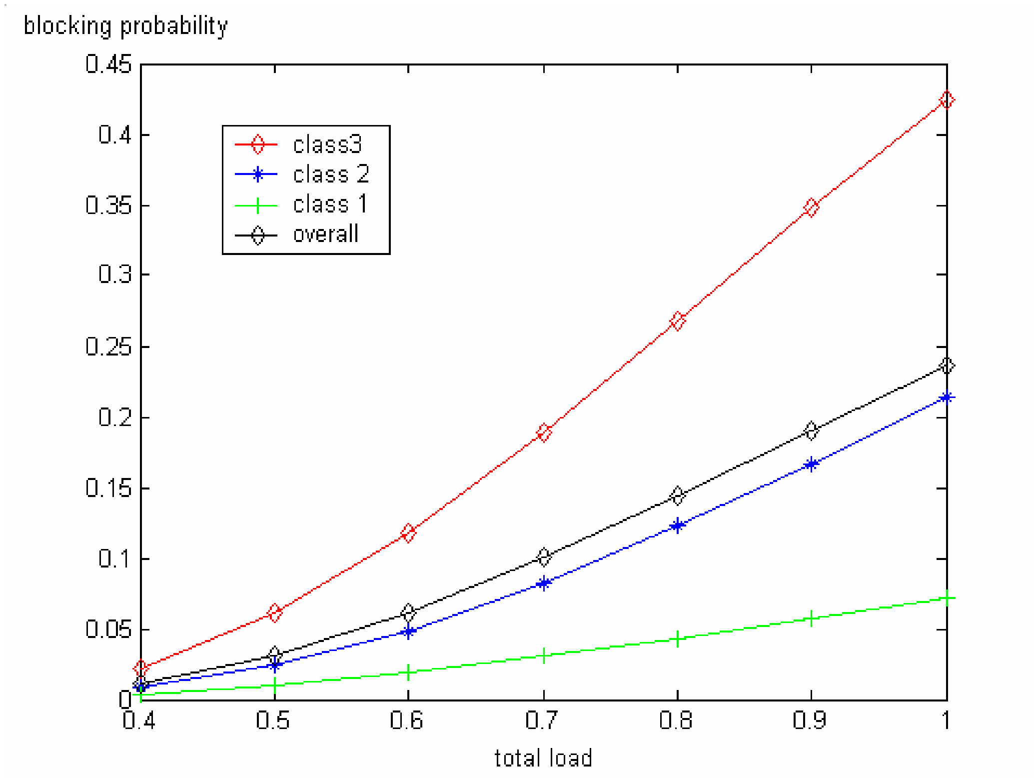


Figure 3-15: total load vs. blocking probabilities with $p_1 = 0.7$ and $p_2 = 0.3$

Clearly, the proposed Probabilistic Preemptive scheme is able to provide service differentiation in OBS networks at different load condition with different settings of p_1 and p_2 in a multi-class system. It also can be observed from the figure that, as load increases, the blocking probabilities of all three classes increase. However, we notice that the increasing rates of blocking probability of the three classes are different.

3.4.3 System Utilization and Transmission Effectiveness

Here again, the transmission effectiveness is defined as the percentage of the total transmission time of bursts successfully passing through the switching node over that of all bursts arriving at the switching node. That is also the total length of bursts successfully passing through over that of all bursts arriving at the switching node.

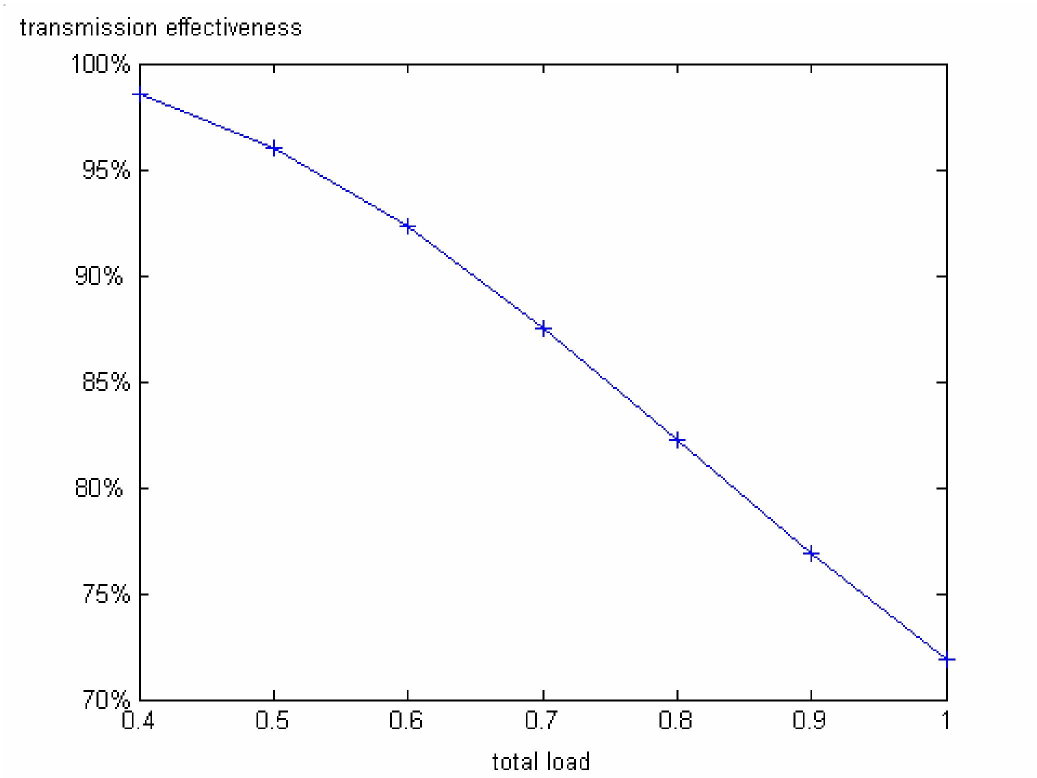


Figure3-16: Transmission effectiveness vs. total load

Figure 3-16 shows the transmission effectiveness vs. overall offered load changes when the preemptive probability p (= p_1 = p_2) is set to be 0.8. It is shown in the figure that the transmission effectiveness drops when the total offered load increases. When the load is 0.4, the transmission effectiveness almost reaches 100%. This is because at the light load condition, the blocking probabilities of both classes are very small. However, when the load is 1, the transmission effectiveness decreases to 72%. This is caused by more blocking of low priority class bursts when the load is increased. When the preemption takes place, the low priority burst with a longer packet length may have to be dropped. This results in a drop in the transmission effectiveness. However, as observed for the two-class case in section 3.3.4, even at this worst case, our probabilistic preemptive scheme still can achieve 72% transmission effectiveness in a three-class system.

As before, the system utilization is the percentage of the total transmission time of bursts successfully passing through the switching node over the total simulation time multiplied by the number of wavelengths.

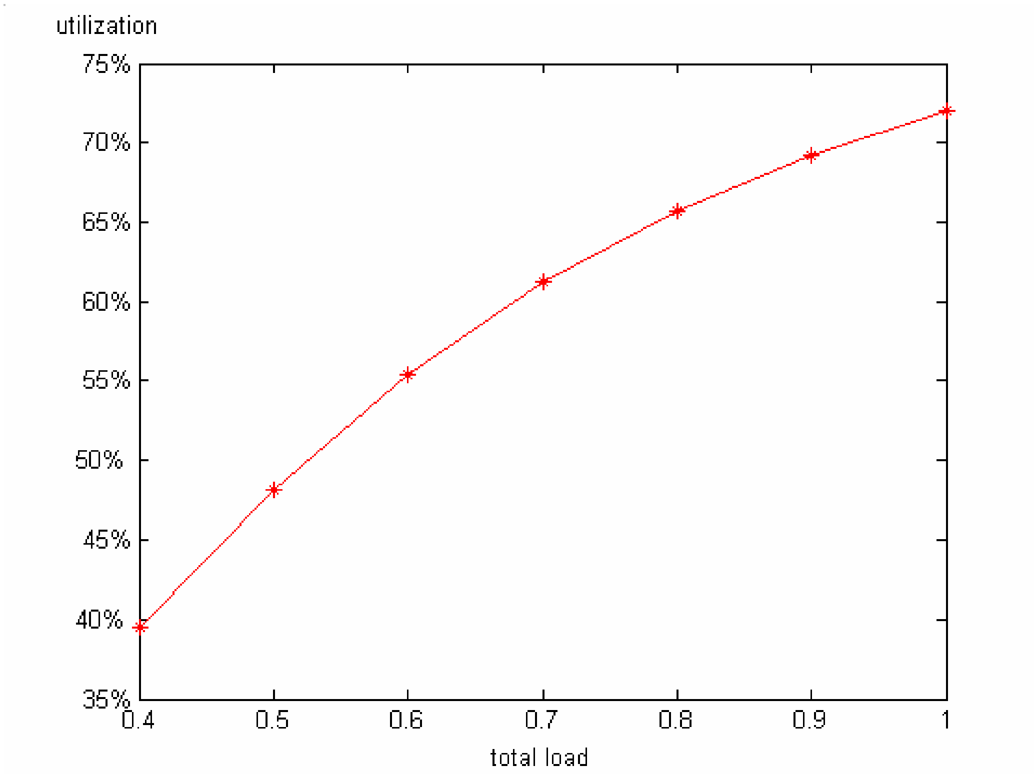


Figure 3-17: system utilization vs. total load

Figure 3-17 shows the system utilization vs. the total offered load when the preemptive probability *p* is set to be 0.8. The figure shows that the system utilization increases when the total offered load increases. That is what we expect. When the load is 0.4, the system utilization is just 40%. This is because at the light load condition, the wavelength resource is not fully utilized. However, when the load is 1, the system utilization increases to 72%. This is because more bursts are transmitted on the wavelengths and the three-class system is much more utilized.

Figure 3-18 shows the transmission effectiveness and system utilization vs. preemptive probability p (= p_1 = p_2) when the total offered load is set to be 0.9. We can see from the figure that when the preemptive probability p increases from 0 to 1, both transmission effectiveness and system utilization slightly decrease. This is because when more preemptions take place, more low priority bursts are dropped.

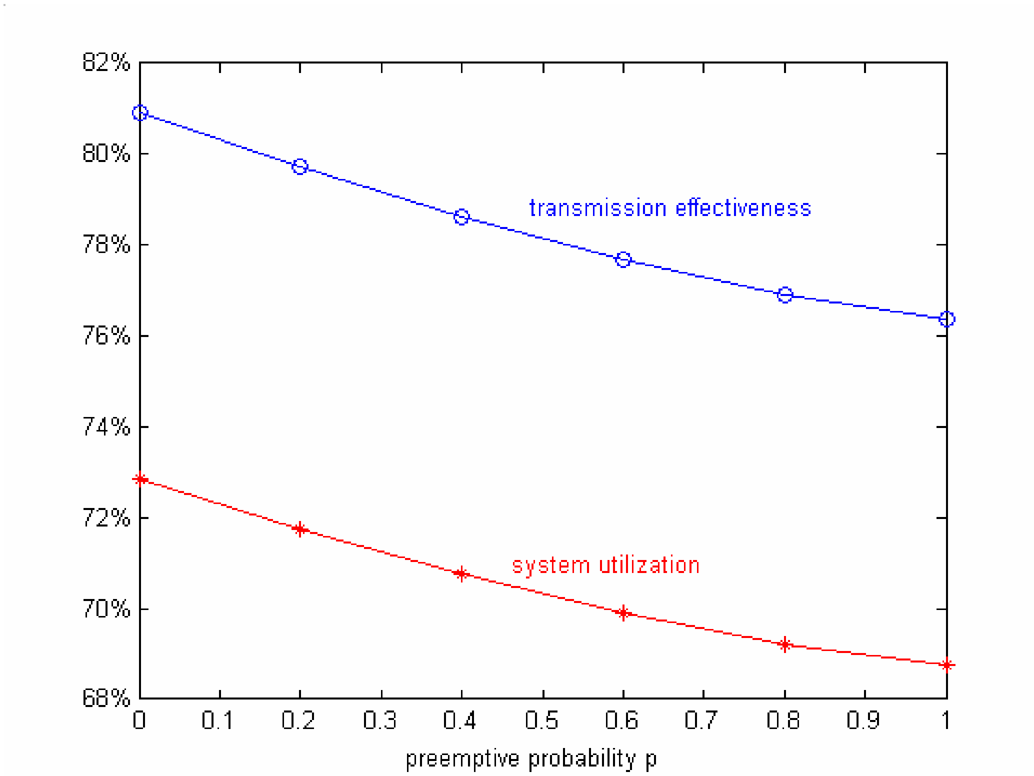


Figure 3-18: transmission effectiveness and system utilization vs. p

From the Figures 3-16, 3-17 and 3-18, it can be seen that the change of total offered load has large impact on both the transmission effectiveness and the system utilization when the preemptive probability p is fixed. However, if the total offered load is fixed, the preemptive probability p just has a relatively small impact on the transmission effectiveness and the system utilization in the three-class system.

3.5 Summary

In this chapter, a Probabilistic Preemptive scheme has been proposed to provide efficient support for service differentiation at the WDM layer in OBS networks. In addition, various aspects of the proposed Probabilistic Preemptive scheme have been studied. First, for the two-class system, the impact of preemptive probability on blocking probabilities of the two classes and the blocking ratio of two classes were shown in simulation results. The overall performance of the two-class system in terms of overall blocking probability was theoretically analysed and compared with simulation results. These results show that Probabilistic Preemptive scheme is effective in achieving adjustable service differentiation without degrading the overall performance in terms of blocking probability, i.e., the proposed scheme has the conformance to the conservation law. The simulation results have also shown that the preemptive probability just has slightly impact on system utilization and transmission effectiveness.

Second, for the multiple class system, a three-class system was studied as an example. The simulation results have shown the impact of preemptive probability on blocking probabilities of the three-class system. These results also show that Probabilistic Preemptive scheme is effective in achieving adjustable service differentiation. By comparing the simulation results of overall blocking probabilities, it is shown that the conservation law still holds in the multiple class system when Probabilistic Preemptive scheme is adopted.

In conclusion, the presented results show that the proposed scheme can provide effective support of service differentiation in OBS network. In addition, the proposed scheme conforms to the conservation law. The simulation results also show that the proposed scheme can provide satisfactory transmission effectiveness and system utilization. Moreover, the proposed Probabilistic Preemptive scheme does not need optical buffer, nor does it introduce additional burst delay.

Chapter 4: The Multi-node System

4.1 Overview

In the previous chapter, the system performance of the single node case has been examined. In this section, we will discuss the case where the proposed Probabilistic Preemptive scheme is applied in a multi-node system. In the multi-node system, signalling issue becomes an important problem when the Probabilistic Preemptive scheme is adopted. A signalling method is needed when the preemption is successful at a switching node by using the proposed Probabilistic Preemptive scheme. This is because the downstream nodes need to be informed the preemption information.

When the preemption takes place, the preempted burst header has already been sent out to the following nodes. The preempted burst header will still try to reserve the time periods for the preempted burst at the following nodes since it does not know about the preemption, which happened at the upstream nodes. This will cause the waste of the wavelength resource. Thus, the following nodes need to be notified the preemption information at the upstream node, so that they can change their wavelength reservation to accommodate more bursts.

4.2 Signalling Issue

The signalling problem will be explained using an OBS network segment. Figure 4-1 shows the OBS network segment, which consists of 6 adjacent OBS switching nodes.

Bursts in the network are classified into two classes: high priority class and low priority class. Each node implements the Probabilistic Preemptive scheme. There are three flows going through this network segment, which are Flow 0 (F0), Flow 1 (F1) and Flow 2 (F2). F0 has the longest path (5 hops) on this network segment, while F1 and F1 just have 1 hop to travel. Let us assume that the bursts in both F0 and F2 belong to the low priority class, and the bursts in F1 belong to the high priority class. In this situation, the problem of wasting wavelength resource comes out.

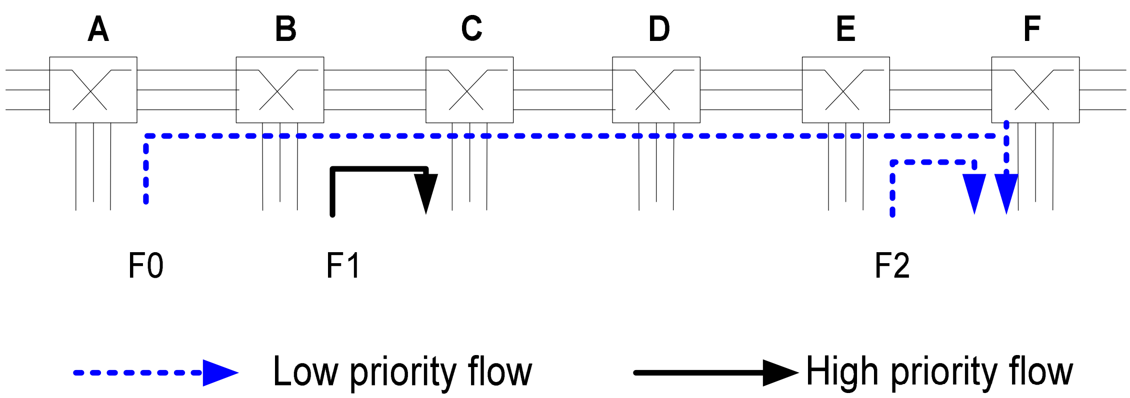


Figure 4-1: OBS network segment

When a high priority burst header of F1 arrives at Node B, if it cannot find a suitable wavelength period for its burst, suppose it will preempt a low priority burst of F0. When this preemption takes place, the preempted burst header of F0 has already been sent out to reserve the wavelength periods at the following nodes, Node C, Node D… etc. Since the low priority burst of F0 has already been dropped at the Node B, the wavelength periods reserved at the following nodes will be wasted. Consequently, in this case, the low priority bursts of F2 may also be affected. The requests of wavelength reservation by low priority bursts of F2 are possibly rejected at Node E due to the wavelength allocated to the F0 burst, which has already been preempted. Such cases will result in the blocking probability of F2 to be increased and the system utilization of the whole network segment to be decreased.

Similar problems arise in networks with more generic topologies. Here we just demonstrate in a simplified chain network case. The chain network can indeed be treated as a fraction of a general OBS network. For the simulations presented in the next subsections, this kind of chain network is used.

To solve the resource wastage problem due to preemption, a signalling protocol may be used to tell the following nodes to release resources reserved by a burst that has been preempted at some upstream node. For the signalling, there are two possible ways. The first one is to relate the routing information with the preempting action. It means when preemption needs to be done, select the low priority class burst, which has the same routing path as the high priority class burst with the largest same number of hops. By doing so, the downstream nodes will be notified the preemption by just adding additional information in the header for the high priority class burst which preforms the preemption. The following switching nodes can then change their reservation accordingly based on this information when the high priority header arrives.

The second way is to use an additional release header (REL) to inform the downstream nodes about the preemption. When preemption takes place at a switching node, this switching node will generate a new release header. The release header contains the information about the preempted burst, such as its starting time, the burst length, the burst ID, the source ID and destination ID, as well as the outport from the current switching node. Actually it contains almost the same information as the preempted burst. The difference is that it has one bit to indicate that it is a release header.

The second way is the one adopted in this thesis. This is because the low priority burst with the largest same number of hops of the same routing path as the high priority burst is selected when using the first way. However, it is possible that there is no low priority burst with the same routing path as the high priority burst. Consequently, the high priority burst has to preempt a low priority burst, which does not have the same routing path. As a result, the preemption that has happened at the upstream node cannot be known by the downstream nodes. Since the release header is adopted in the second way, the downstream nodes will always be informed of the preemption by the release header.

With the second way, after the preemption happens, the release header will be sent out to inform the downstream nodes. When the release header arrives at the downstream nodes, it will release the wavelength periods that have been reserved for its corresponding preempted burst. Thus those periods would be available to other requests. The utilization of wavelength resource will be maximized. Here it is assumed that the network topology and the routing policy of the headers not change in the considered period, and thus the release header can reach all the downstream nodes of its preempted burst.

There are two possible cases when a release header arrives at the next switching node:

Case 1: The switching node successfully finds the reserved time period for the preempted burst based on the information of the released header. In this case, the switching node can delete the reservation made for the preempted burst. If the release header does not reach its destination, it will be transmitted to the next switching node. If the release header reaches its destination node, it is simply dropped.

Case 2: The switching node cannot find the reserved time period for the preempted burst. This may be caused by that the time period has already been preempted by another high priority class header, which passes through this node. Under this case, the release header will still be transmitted to the next switching node, until it reaches its destination node where it is dropped.

4.3 Performance Comparisons

In this section, the performance improvement of the Probabilistic Preemptive scheme with the introduction of the release header in an OBS chain network will be investigated. The improvement is defined in Equation 4-1.

$$improvement = \frac{Blocking_n - Blocking_r}{Blocking_n} \times 100\% \qquad (4\text{-}1)$$

$Blocking_n$: Blocking probability without release header

$Blocking_r$: Blocking probability with release header

For the investigation, it is assumed that there are two classes of traffic in the network, which are high priority class and low priority class. In addition, each node implements the Probabilistic Preemptive scheme. Simulations are conducted to show the improvement of the burst blocking probabilities of both high and low priority when we adopt the use of the release header under different network conditions. Different sets of flows on the network segment are used to simulate the different network conditions in the following subsections.

For the simulations presented in the following sub-sections, it is assumed that in each traffic flow, the load of high priority class is half of the load of the low priority class. Each transmission link consists of 16 channels. Both the burst length and burst inter-arrival time of each flow are assumed to be exponentially distributed. Different flows are assumed to generate bursts at the same average rate and have the same average burst service time, which is 1.

4.3.1 Impact of Preemptive Probability *p*

The network segment in Figure 4-2 is used for simulations in this subsection. The flows are set as shown in Figure 4-2. The burst blocking probabilities' improvement of each flow with the use of release header under different preemptive probability p conditions will be compared. The load of each flow is set to be 0.35. The load of the low priority class is twice of the load of the high priority class in each flow. There are only two classes traffic used in this project. Since each link is shared by two flows, each link has the load of 0.7. The preemptive probability p changes from 0 to 1.0.

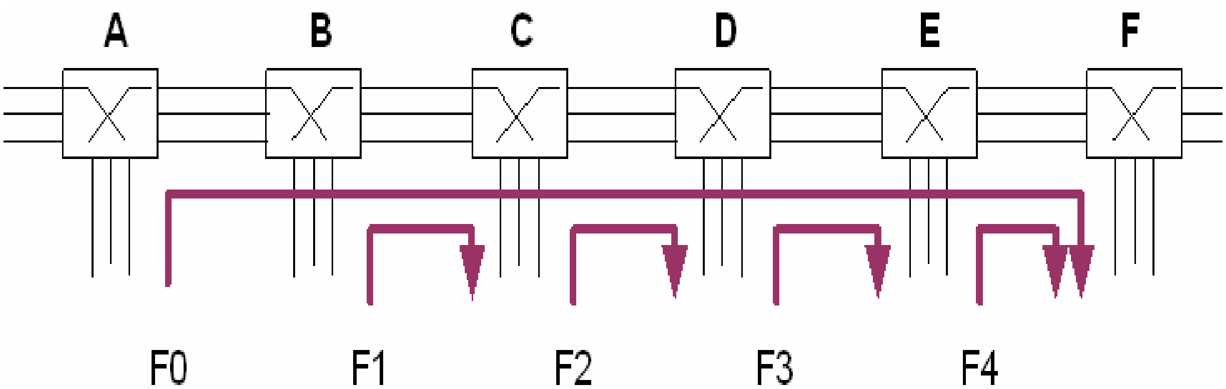


Figure 4-2: Network segment in simulation

The initial offset time between a header and its corresponding data burst for each flow is set as Δ*H, where Δ is the maximal header processing time at each switching node. Δ is set to be 10 in our simulations and H is the number of hops the burst will travel. Here in this particular chain network case, the offset time is set to be 5Δ for Flow 0, and the offset time of all the other flows as Δ. This is the case that all the flow traffic ends at their egress nodes of this chain network.

Figures 4-3 and 4-4 plot the improvement on burst blocking probabilities versus preemptive probability *p* for high priority and low priority bursts respectively. It is shown that for both high and low priority classes, Flow 4 has the most significant improvement on burst blocking probabilities. This is what we expect. When a low priority class burst gets preempted by a high priority class burst at an upstream node, a release header is generated. This release header will try to cancel all the reservations made by the low priority header on all the downstream nodes. The burst blocking probabilities of Flow 4 are affected by all the upstream flows, i.e., Flow 0, Flow1, Flow 2 and Flow 3. The less channels, or wavelengths, the upstream flow reserves, the more resources will be available for Flow 4 and hence the lower blocking probabilities. In conclusion, the most significant improvement on burst blocking probabilities happening on Flow 4 is due to an accumulated effort of all release headers generated by all the upstream flows.

Flow 1 has the minimum improvement in burst blocking probabilities since only Flow 0's release headers can have effect on it due to its relative upstream position in the network segment. Flow 3 has better improvement than Flow 2 since one more flow's release headers can have effort on it due to its relative downstream position in the network segment.

Figures 4-3 and 4-4 also show that the improvements on burst blocking probabilities increases when the preemptive probability p increases. This is because when the preemptive probability p increases, more preemptions take place. This results in the amplifying effect of release headers, and hence better improvement of burst blocking probabilities.

We observe that the improvement on high priority class blocking probability is higher than the improvement on low priority class blocking probability. This is because the release headers free the preempted burst periods at the downstream nodes. As a result, both high priority class bursts and low priority class bursts will get more chances to be accepted. However, the high priority class will have better improvement since the high priority class bursts will have more opportunities to preempt low priority bursts.

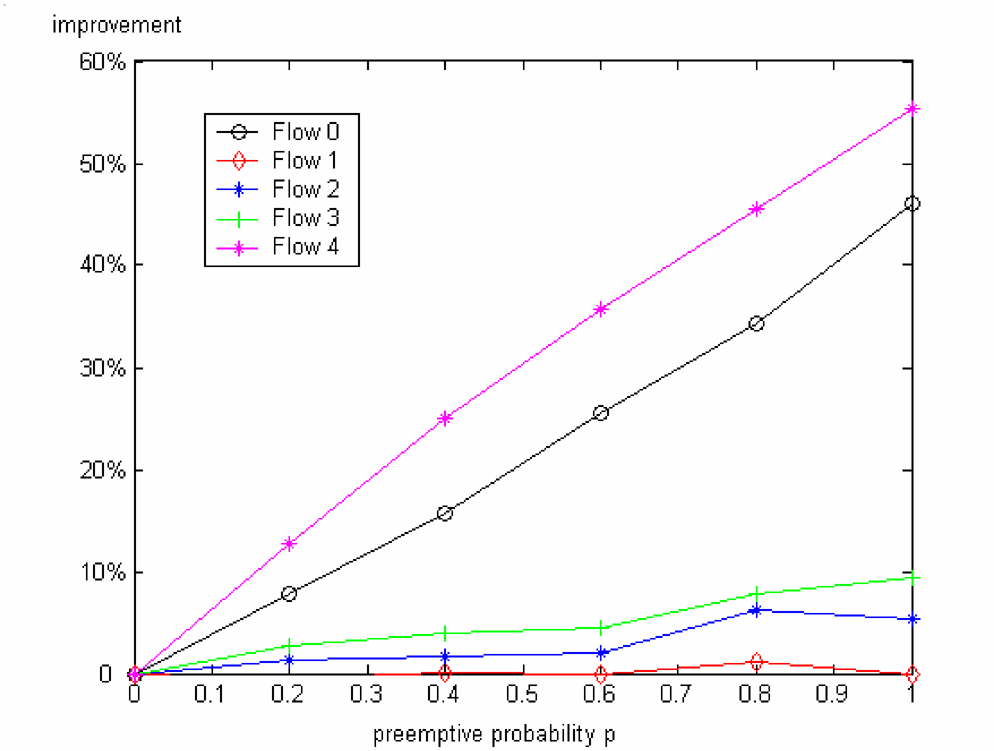


Figure 4-3: Improvement on high priority class when *p* changes and load is fixed

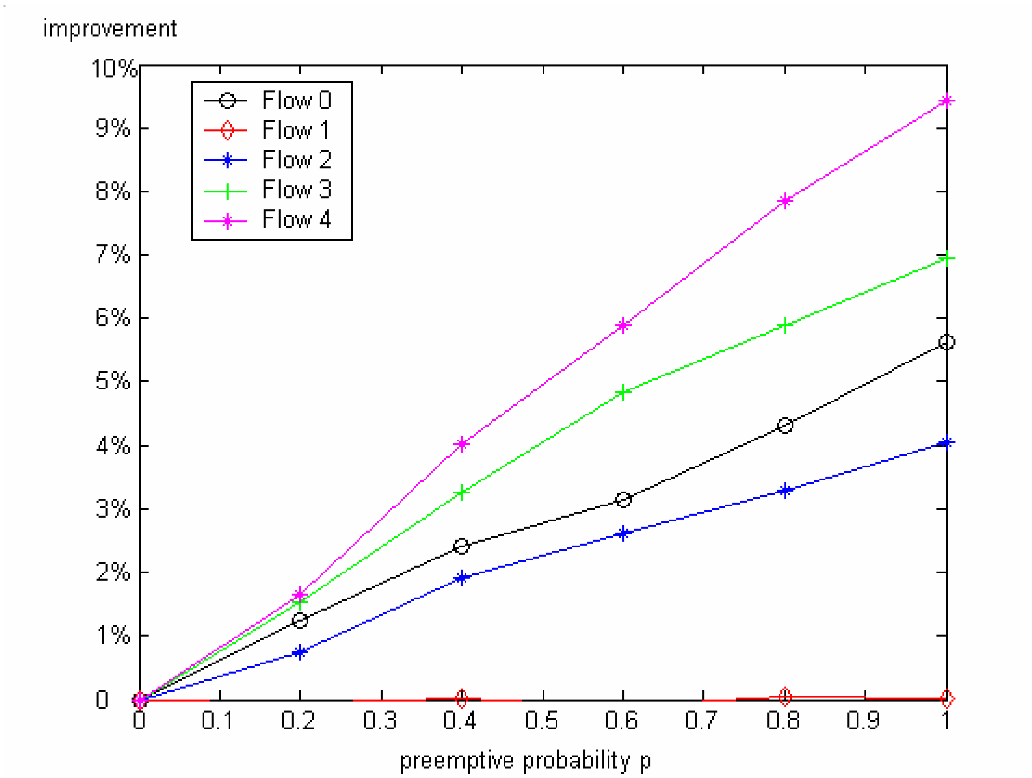


Figure 4-4: Improvement on low priority class when *p* changes and load is fixed

4.3.2 Impact of load

In this subsection, the network segment in Figure 4-2 is again used for simulations. The flows are set as shown in Figure 4-2. The burst blocking probability improvement of each flow with the use of release header under different load conditions is compared when the preemptive probability *p* is fixed. Each link is shared by two flows, and each flow is assumed to provide half of the total load on the link. In this subsection, the range of total load is chosen to be from 0.4 to 1.0. The preemptive probability *p* is set as 1.0, i.e., the preemption takes place whenever it is needed. The same offset time settings for the flows as what have been used in Section 4.3.1 are adopted.

Figures 4-5 and 4-6 plot the improvements on burst blocking probabilities versus total load on each link for high priority and low priority respectively. It is observed that for both high and low priority, Flow 4 still has the most significant improvement on burst blocking probabilities. Flow 1 has the least improvement on burst blocking probabilities. This is expected. The reason is the same as what has been explained in Section 4.3.1.

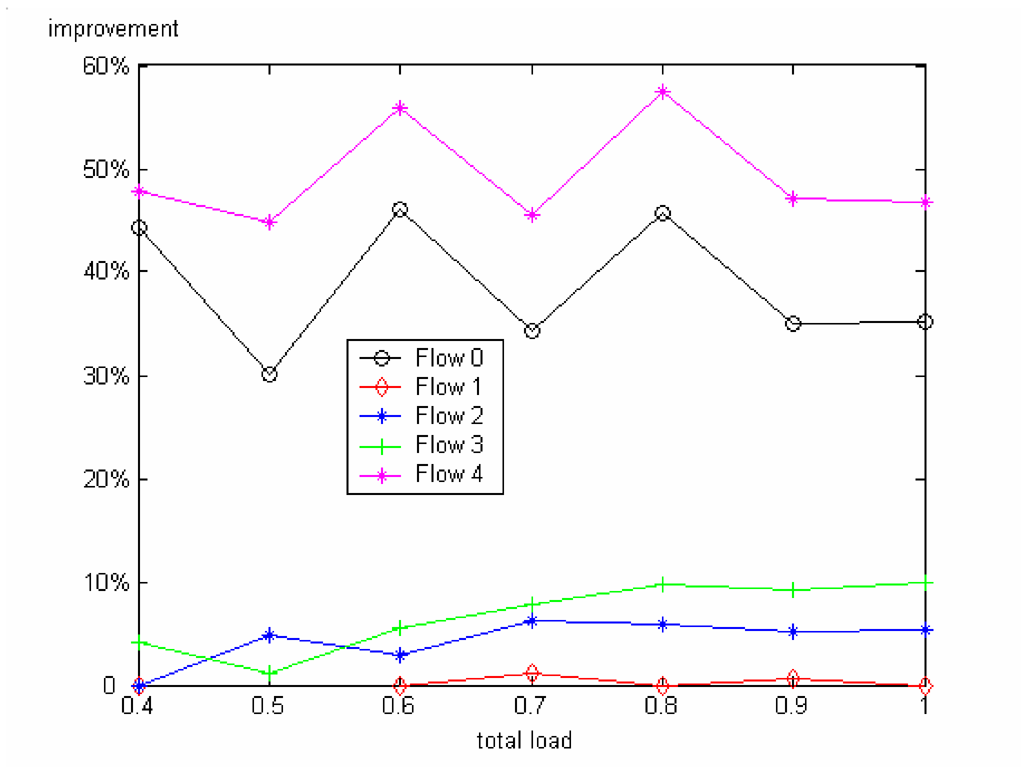


Figure 4-5: Improvement on high priority under different load condition

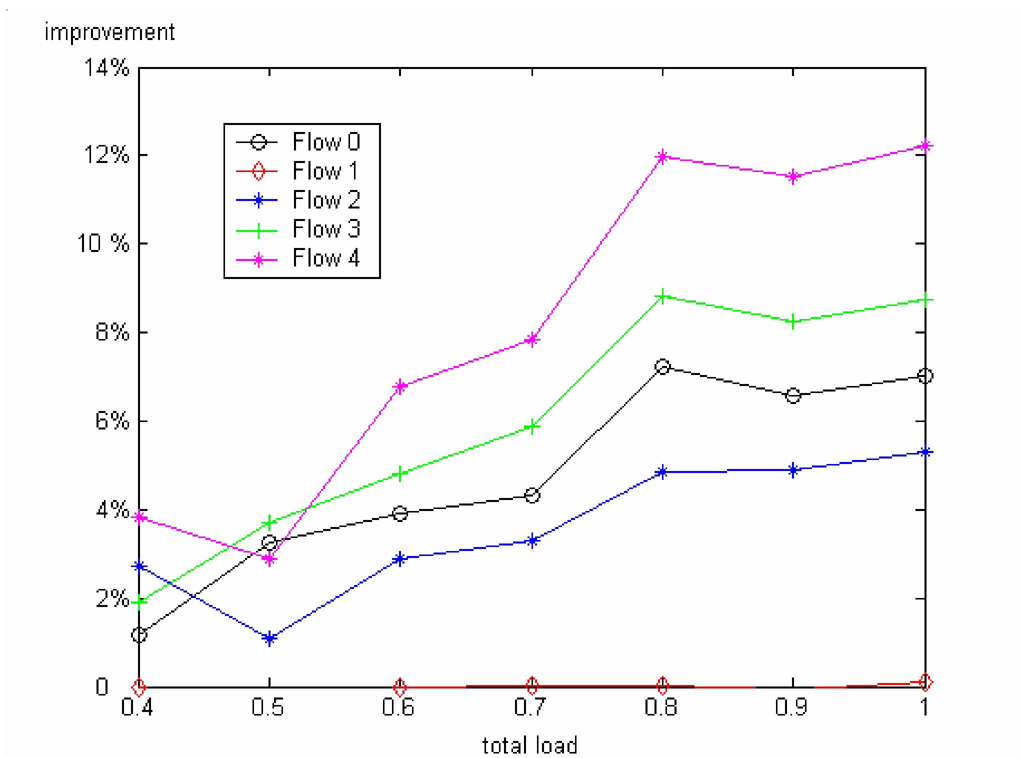


Figure 4-6: Improvement on low priority under different load condition

Figures 4-5 and 4-6 show that the improvements on burst blocking probabilities vary when the total load on each link changes. At the different load conditions, the improvements on the burst blocking probabilities are different. For example, the improvement on the high priority class bursts of Flow 4 varies between 45% and 60%. The improvement on low priority class bursts of Flow 4 varies between 3% and 12%. Figures 4-5 and 4-6 also show that the improvement on high priority class blocking probability is much higher than the improvement on low priority class blocking probability. This is because the high priority class bursts will have more opportunities to preempt the low priority class bursts as explained in Section 4.3.1.

4.3.3 Impact of offset time

In this subsection, the effect of offset time on the performance improvement will be discussed. The same flow settings as shown in Figure 4-2 are used in the simulation. However, the offset time settings for the flows are different from the previous two subsections. The burst blocking probability improvement of each flow with the use of release header under different load conditions will be compared when the preemptive probability p is fixed. Again, each link is shared by two flows, and each flow is assumed to provide half of the total load. In this subsection, the range of total load on each link is chosen to be from 0.5 to 1.0. The preemptive probability p is set as 1.0, i.e., the preemption takes place whenever it is needed.

The initial offset time between a header and its corresponding data burst for each flow is set as Δ*H, where Δ is the maximal header processing time at each switching node, set as 10 in our simulations and H is the number of hops the burst will travel. Here three cases are considered. In Case 1, the offset time of Flow 0 is set to be 5Δ, and the offset time of all the other flows are Δ. This is the case that all flows end at their egress nodes of this chain network. In Case 2, Flow 0 to 4 have the offset time of 5Δ, 4Δ, 3Δ, 2Δ and Δ respectively. This is the more generic case, where some flows reach the destination, and the other flows pass through their intermediate nodes. In Case 3, all flows have the same offset time of 5Δ. This is the case that all the flows have the same number of remaining hops, when they enter the network segment shown in Figure 4-2.

Figures 4-7, 4-8, 4-9, 4-10 and 4-11 plot the improvement on burst blocking probabilities versus load for Flow 4, Flow 3, Flow 2, Flow 1 and Flow 0 respectively. It is shown that the change of offset time has no significant impact on the improvement of burst blocking probabilities. It can be observed that the change of offset time has slightly more impact on the improvement of high priority than that of low priority for all the flows.

For both priorities, the impact on the improvement of the three cases changes when the total load condition on each link varies. For example, at the some load condition, Case 1 may have the slightly better improvement than the other two cases and vice versa. For the high priority of Flow 4, at load 0.5, Case 2 has a bit better improvement than the other two cases. However, at load 0.8, Case 2 has worse improvement than the other two cases. Thus it cannot be concluded which case gives the best performance improvement since it will vary with the change of load. In conclusion, the change of offset time settings does not have great impact on the improvement of burst blocking probabilities.

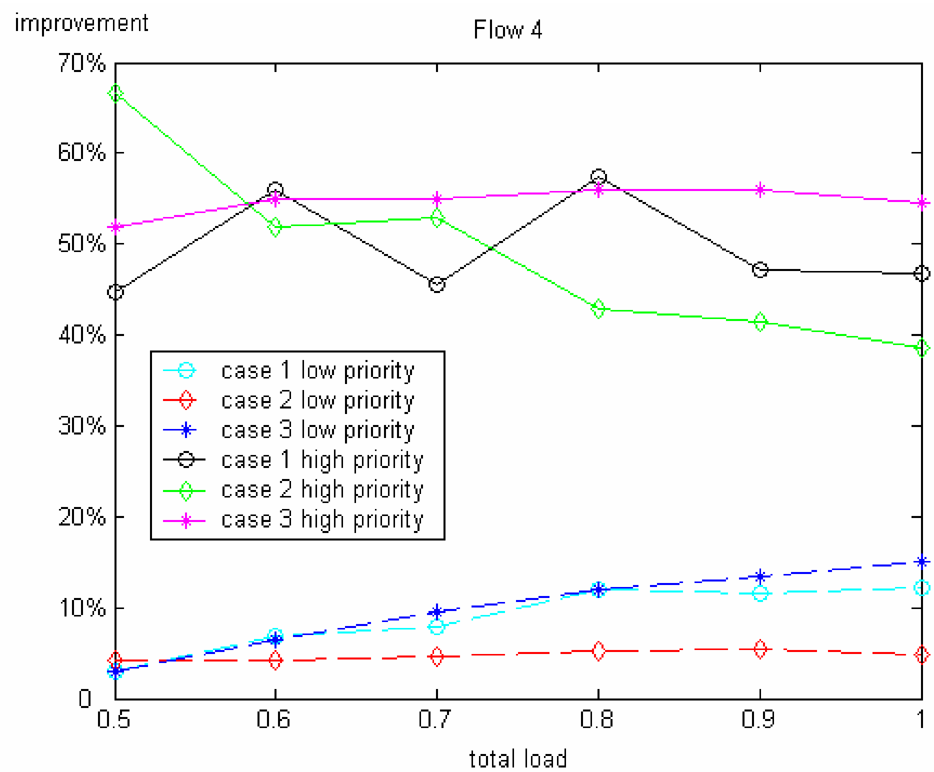


Figure 4-7: Improvement of Flow 4 under different offset time condition

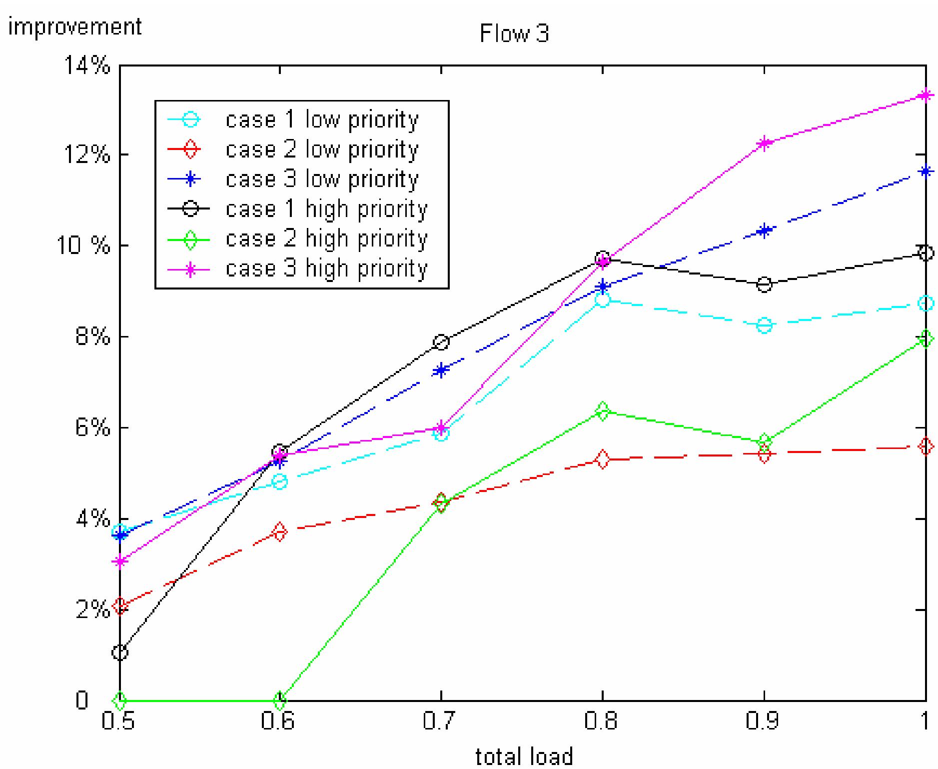


Figure 4-8: Improvement of Flow 3 under different offset time condition

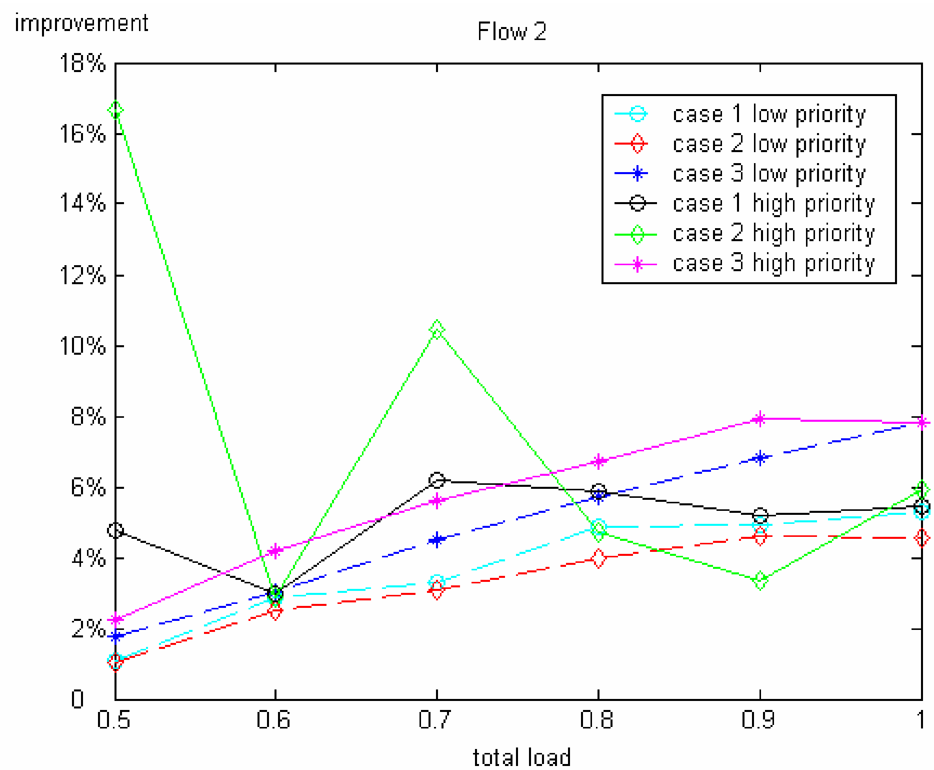


Figure 4-9: Improvement of Flow 2 under different offset time condition

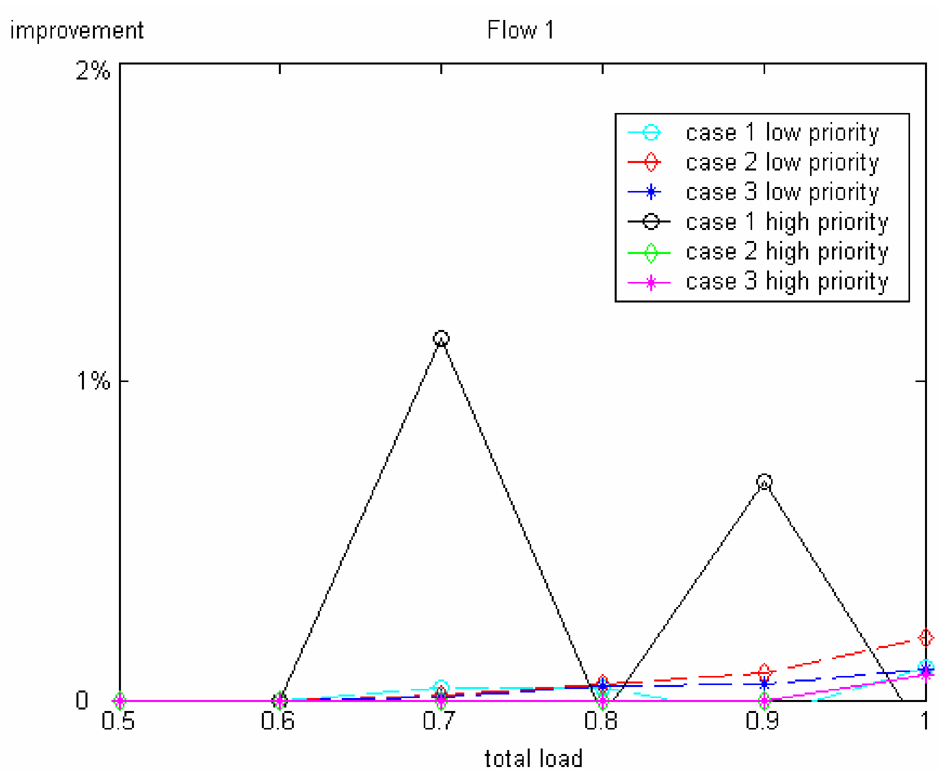


Figure 4-10: Improvement of Flow 1 under different offset time condition

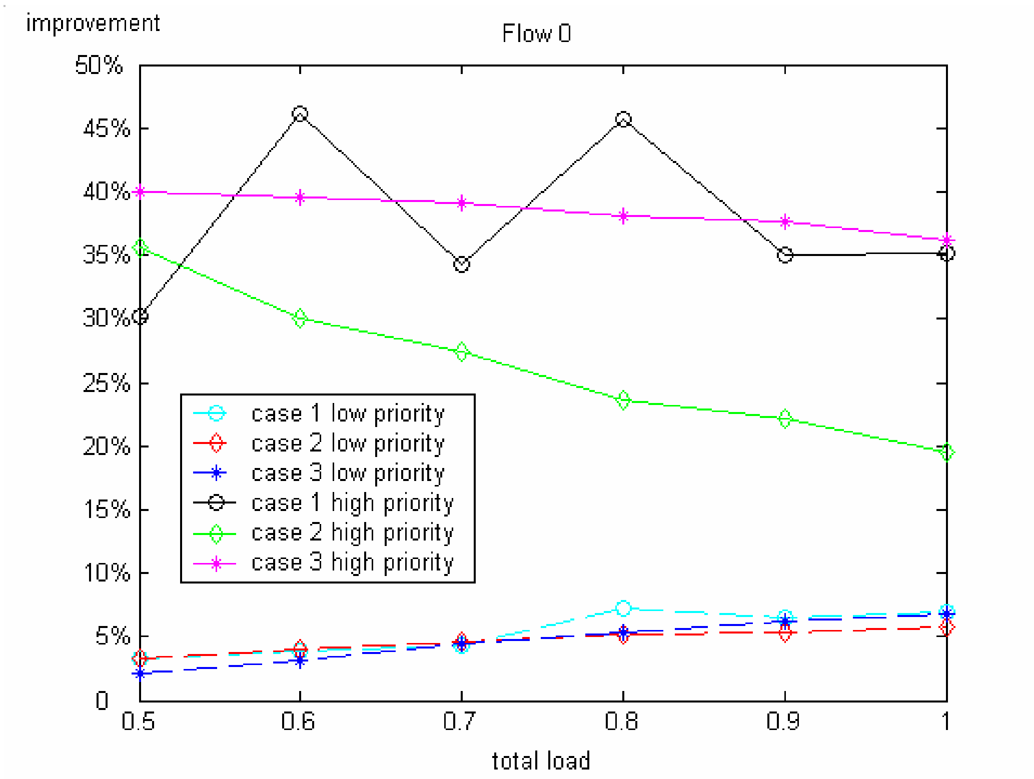


Figure 4-11: Improvement of Flow 0 under different offset time condition

4.3.4 Impact of connections

In this subsection, the effect of different connections on the network segment on the performance improvement will be discussed. The flow setting as shown in Figure 4-12 is used in the simulations for this subsection. In this network segment, all flows are set to end at Node F. The load on each link is different. The same offset time settings as what have been used in Section 4.3.1 will be used.

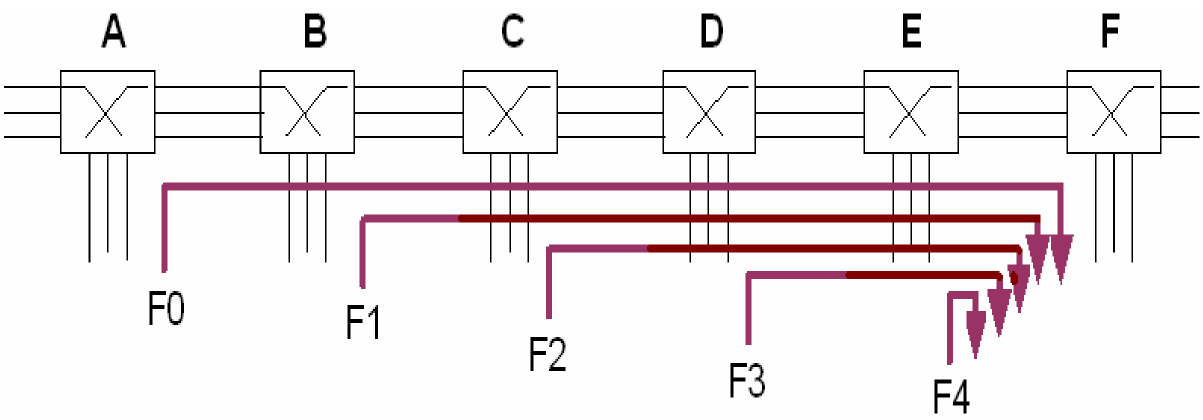


Figure 4-12: Network segment in simulation

In Figures 4-13 and 4-14, the burst blocking probability improvements of each flow with the use of release header are compared when the preemptive probability *p* varies and the load of each flow is fixed to 0.2. Figures 4-13 and 4-14 show that for both high priority class and low priority class, all the flows have almost the same improvements in terms of burst blocking probabilities even when the preemptive probability *p* changes. This is because of the reason as shown below.

When a low priority class burst gets preempted by a high priority class burst at an upstream node, a release header is generated. This release header will try to cancel all the reservations made by the low priority header on all the downstream nodes. Since all flows end at the Node F, each single flow is affected by all the other flows no matter what relative position it is in this network segment. For example, the burst blocking probabilities of Flow 2 are affected by all the other flows, i.e., Flow 0, Flow1, Flow 3 and Flow 4. Thus, the improvements in terms of burst blocking probabilities on Flow 2 are an accumulated effort of all release headers generated by all the other flows. The same conclusion can be applied to all the other flows. This is the reason why they have almost same improvements on burst blocking probabilities.

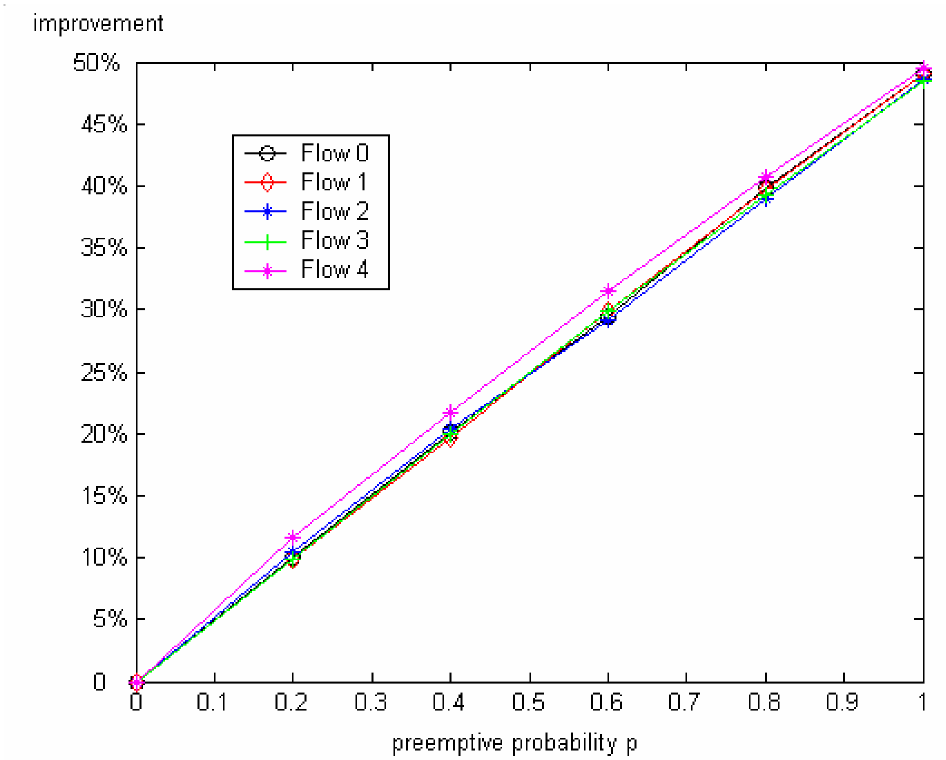


Figure 4-13: Improvement of high priority class when load is fixed and *p* changes

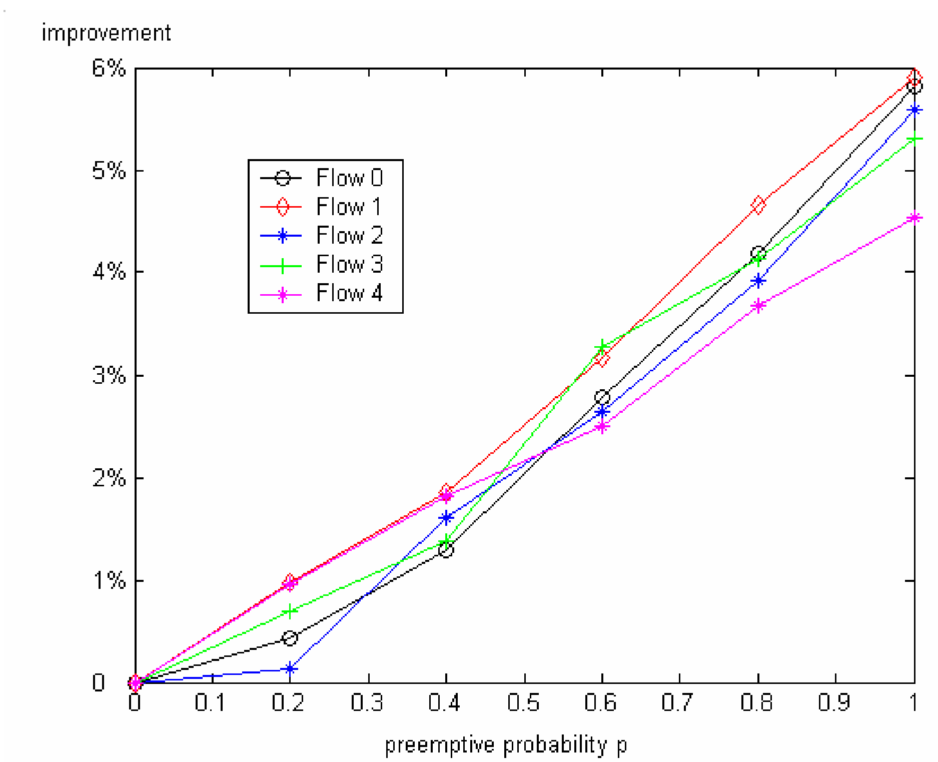


Figure 4-14: Improvement of low priority class when load is fixed and *p* changes

Figures 4-13 and 4-14 also show that the improvements of burst blocking probabilities increases when the preemptive probability *p* increases. This is because when the preemptive probability *p* increases, more preemptions take place and hence more performance improvements.

The improvement of high priority class blocking probability is much higher than the improvement of low priority class blocking probability as shown in Figures 4-13 and 4-14. This is because the release headers free the preempted burst period at the downstream nodes, both high priority class bursts and low priority class bursts will get more chances to be accepted. However, the high priority class will have better improvement since the high priority class bursts will have more opportunities to preempt low priority bursts.

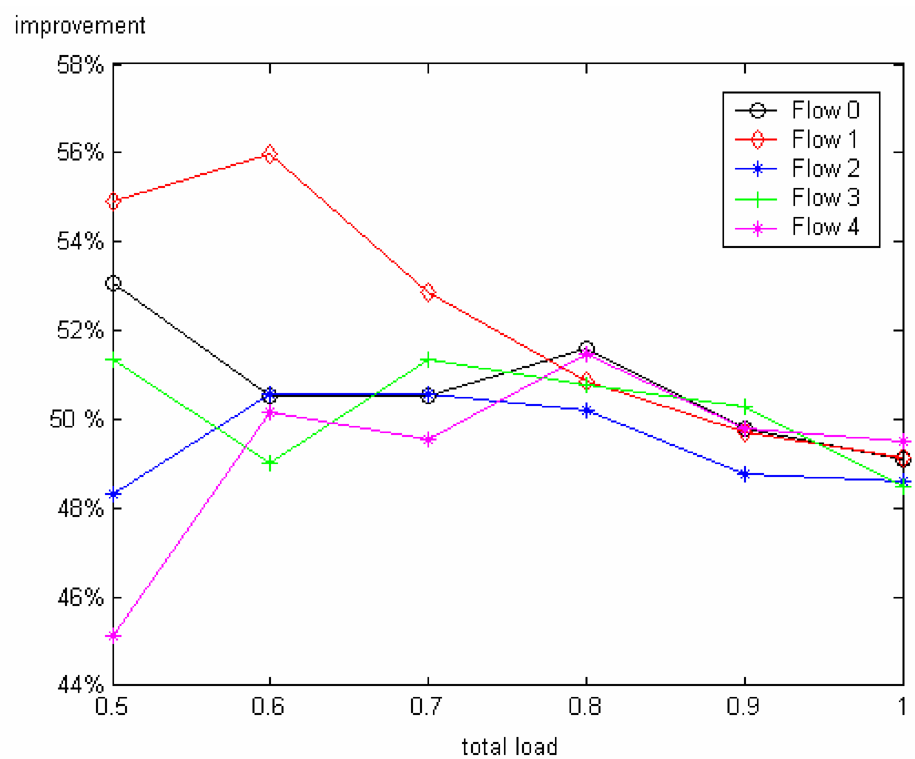


Figure 4-15: Improvement of high priority class when *p* is fixed and load changes

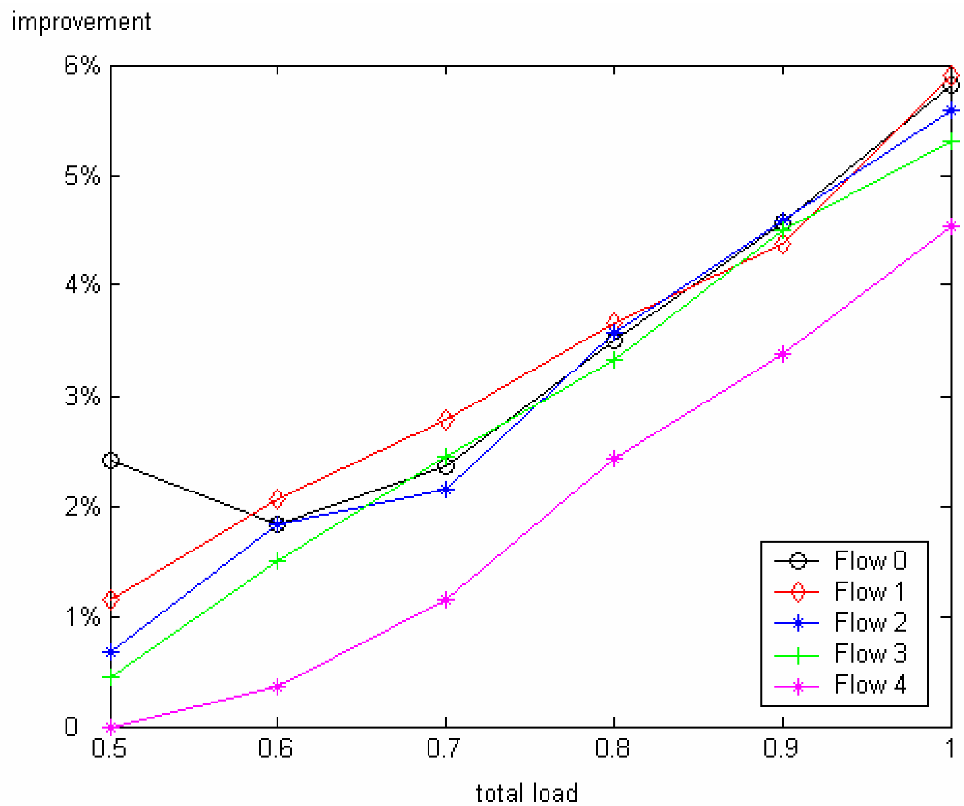


Figure 4-16: Improvement of low priority class when *p* is fixed and load changes

In Figures 4-15 and 4-16, the burst blocking probability improvement of each flow with the use of release header are compared when the preemptive probability *p* is fixed to 1.0 and the load of each flow changes from 0.1 to 0.2. Figures 4-15 and 4-16 show that for the high priority class, the difference between the improvements of all the flows becomes smaller when the total load increases. This is what can be expected.

As discussed earlier, since all flows end at the Node F, each single flow is affected by all the other flows no matter what relative position it is in this network segment. Thus, the improvements in terms of burst blocking probabilities on any flow can be thought as an accumulated effort of all release headers generated by all the other flows. When the load is small, the preemptions take place rarely. Thus the effect of release header is rather random. When the load increases, the preemptions happen more often. The effect of the release header becomes obvious and stable. This is the reason why all flows have almost the same improvements on burst blocking probabilities at the heavy load condition.

4.4 Summary

In this chapter, the signalling issues are discussed when the proposed Probabilistic Preemptive scheme is applied in an OBS network. A solution has been presented to solve the signalling problem, in which release header is used to release the reserved periods of a preempted burst in the following nodes of the network. The performance of the system with or without releaser header are simulated and compared.

Various factors' impacts on the performance improvement when the release header is adopted are studied through simulations. First, the impact of preemptive probability *p* on the improvement is inspected. Second, the impact of load on the improvement is investigated. Third, the impact of offset time on the improvement is studied through simulations. Finally, the impact of connections is examined.

The simulation results show that when the release header is adopted with the proposed scheme, there will be an improvement on the burst blocking probability, no matter it is high priority or low priority. In addition, normally, the improvement on high priority is higher than that on low priority.

Chapter 5 Conclusions and Further Research

5.1 Conclusions

In this thesis, a simple and flexible scheme, called Probabilistic Preemptive scheme, has been proposed to provide efficient support for service differentiation at the WDM layer in OBS networks. The proposed Probabilistic Preemptive scheme is based on the existing preemptive scheme with the difference that a probabilistic parameter is assigned to each high priority class except for the lowest one. This scheme can provide flexible service differentiation by setting the assigned probabilistic parameters properly. In addition, the Probabilistic Preemptive scheme can be easily and exactly reduced to the ordinary preemptive scheme by setting $p_i = 1$. Moreover, the Probabilistic Preemptive scheme does not require the use of buffer at a switching node. Nor does it introduce additional delay.

Various aspects of the proposed Probabilistic Preemptive scheme have been studied in this thesis. First, for the two-class system, the impact of preemptive probability on blocking probabilities of the two classes and the blocking ratio of two classes were shown in simulation results. The overall performance of the two-class system in terms of overall blocking probability was theoretically analysed and compared with simulation results. It is shown that the proposed Probabilistic Preemptive scheme is effective in achieving adjustable service differentiation without degrading the overall performance in terms of blocking probability, i.e., the proposed scheme conforms to the conservation law.

Second, for the multiple class system, a three-class system was studied as an example. The simulation results have shown the impact of preemptive probability on blocking probabilities of the three-class system. It is shown that the proposed Probabilistic Preemptive scheme is effective in achieving adjustable service differentiation in the three-class system. By comparing the simulation results of overall blocking probabilities, it is shown that the conservation law still holds in the multiple class system when Probabilistic Preemptive scheme is adopted.

Third, for the multi-node system, the signalling issue was discussed and solved. A release header was used to remove the switching information of the preempted burst in the downstream nodes of the network. The performance of a two-class system with or without releaser header were simulated and compared. It is shown in the simulation results that with the use of the release header, the bandwidth wastage and the burst blocking probability for both high priority and low priority class reduce. Normally, the improvement on the high priority class is higher than that on the low priority class.

Note that while the proposed scheme provides another option for achieving service differentiation in OBS networks, it does not exclude the integration with other schemes with the same purpose. In fact, all the three schemes reviewed in the Chapter 2 may be integrated with the Probabilistic Preemptive to achieve additional freedom in achieving service differentiation in OBS networks.

5.2 Further Research

While this thesis has proposed the Probabilistic Preemptive scheme, which can provide service differentiation in OBS networks through probabilistic preemption, several issues remain open for further research, which include:

1. Analysis of the multi-class system

In Chapter 3, for the Probabilistic Preemptive scheme, its blocking probabilities analysis in this thesis mainly focuses on the two-class case. The state transition diagrams for two-class system are presented and studied. The blocking probabilities of the single channel system are derived as an example. For the multi-class cases, additional work is needed to derive blocking probabilities for each class.

2. Integration with other schemes

While the performance of the proposed Probabilistic Preemptive scheme has been investigated under various situations in this thesis. However, the investigation is limited to the scheme alone. The proposed Probabilistic Preemptive scheme may be integrated with other schemes. In the further research, an enhanced scheme with the integration of different schemes could be studied.

Author's Publications

- Lihong Yang, Yuming Jiang and Shengming Jiang, "A Probabilistic Preemptive Scheme for Providing Service Differentiation in OBS Networks", *IEEE GLOBECOM 2003*.

Bibliography

[1] N. Gnhani, S. Dixit and T. Wang, "On IP-over-WDM integration", IEEE Communication Magazine, pp. 72-84, March 2000.

[2] C. Qiao and M. Yoo, "Optical burst switching (OBS) - A new paradigm for an optical Internet", Journal of High Speed Networks, vol. 8, pp. 69-84, 1999.

[3] J.S. Turner, "Terabit burst switching", Journal of High Speed Networks, Vol. 8, No. 1, pp. 3-16, 1999.

[4] A. Ge, F. Callegati, L. Tamil, "On optical burst switching and self-similar traffic", IEEE Communications Letters, vol. 4, no. 3, March 2000.

[5] E. Varvarigos and V. Sharma, "The ready-to-go virtual circuit protocol: a loss-free protocol for multigigabit networks using FIFO buffers", IEEE/ACM Trans on Networking, vol. 5, Oct. 1997, pp. 705-718.

[6] I. Widjaja, "Performance analysis of burst admission control protocols", IEEE Proc. Comm., vol. 142, Feb. 1995, pp. 7-14.

[7] M. Yoo and C. Qiao, "A New OBS Protocol for Supporting QoS", in SPIE Proc. of Conf. All-optical Networking, Vol. 3531, pp. 396-405, Nov. 1998.

[8] S. Amstutz, "Burst switching – an introduction", IEEE Communications Magazine, vol. 21, pp. 36-42, Nov. 1983.

[9] H. Zhang, "Service disciplines for guaranteed performance service in packet switching networks", Proc. Of the IEEE, vol. 83, pp. 1374-1396, Oct. 1995.

[10] A. Varma and D. Stilladis, "Hardware implementation of fair queuing algorithms for asynchronous transfer mode networks", IEEE Communications Magazine, vol.35, pp.74-80, 1997.

[11] U. Briem et al., "The traffic management for an ATM switch with per-VC queuing: concept and implementation", IEEE Communications Magazine, vol.36, pp. 88-93, Jan. 1998.

[12] V. Vokkarane, Q. Zhang , J. Jue, and B. Chen, "Generalized Burst assembly and scheduling techniques for QoS Support in Optical Burst-Switched Networks", IEEE GLOBECOM'2002.

[13] Y. Chen, M. Hamdi, and D.H.K. Tsang, "Proportional QoS over OBS networks", IEEE GLOBECOM 2001.

[14] M. Yoo and C. Qiao, "Supporting multiple classes of services in IP over WDM networks", IEEE GLOBECOM'1999.

[15] Y. Jiang, C. K. Tham and C. C. Ko, "A probabilistic priority scheduling discipline for multi-service networks", Computer Communications, Vol. 25, No. 13, pp. 1243 - 1254, 2002.

[16] Y. Jiang, C.K. Tham and C.C. Ko, "Delay analysis of a probabilistic priority discipline", European Trans. On Telecommunications, vol. 13, no. 6, pp. 563-577, 2002.

[17] C. K. Tham, Q. Yao and Y. Jiang, “Achieving differentiated services through multi-class probabilistic priority scheduling”, Computer Networks, vol. 40, no. 4, pp.577-593, 2002.

[18] X. Yu, Y. Chen and C. Qiao, "Performance evaluation of optical burst switching with assembled burst traffic input", IEEE GLOBECOM’2002.

[19] M. Izal, J. Aracil. "On the influence of self similarity on Optical Burst Switching traffic", IEEE GLOBECOM’2002.

[20] 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.

[21] M. Yoo, C. Qiao and S. Dixit, "QoS performance in IP over WDM networks", IEEE JSAC, vol. 18, no. 10, pp. 2062-2071, Oct. 2000.