QUALITY OF SERVICE ENHANCEMENT IN OPTICAL BURST SWITCHING NETWORKS WITHOUT FULL WAVELENGTH CONVERSION CAPABILITY

SHAN DONG MEI

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Shan Dong Mei

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<td>ABR</td>
<td>Aggressive Burst Rescheduling</td>
</tr>
<tr>
<td>AR</td>
<td>Aggressive Rescheduling</td>
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<tr>
<td>ATM</td>
<td>Asynchronous Transfer Mode</td>
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<td>BORA</td>
<td>Burst Overlap Reduction Algorithm</td>
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<td>CAS</td>
<td>Conversion Avoidance Scheduling</td>
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<tr>
<td>CR</td>
<td>Conservative Rescheduling</td>
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<tr>
<td>E/O</td>
<td>Electrical/Optical</td>
</tr>
<tr>
<td>FDL</td>
<td>Fibre Delay Line</td>
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<tr>
<td>FF</td>
<td>First Fit</td>
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<tr>
<td>FFTE</td>
<td>First Fit Based On Traffic Engineering</td>
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<tr>
<td>FWC</td>
<td>Full-Range Wavelength Converter</td>
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<tr>
<td>GEANT</td>
<td>Gigabit European Academic Network</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
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<tr>
<td>ILP</td>
<td>Integer Linear Programming</td>
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<tr>
<td>IM</td>
<td>Input Module</td>
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<tr>
<td>JET</td>
<td>Just-Enough-Time</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>JIT</td>
<td>Just-In-Time</td>
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<td>LAUC</td>
<td>Latest Available Unused Channel</td>
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<td>LAUC-VF</td>
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<td>LSP</td>
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<td>MPLS</td>
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<td>NP</td>
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<tr>
<td>NSFNET</td>
<td>National Science Foundation Network</td>
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<td>OBS</td>
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<tr>
<td>OCS</td>
<td>Optical Circuit Switching</td>
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<tr>
<td>ODBR</td>
<td>On-Demand Burst Rescheduling</td>
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<tr>
<td>OM</td>
<td>Output Module</td>
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<td>OPS</td>
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<tr>
<td>WCB</td>
<td>Wavelength Converter Bank</td>
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<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
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<tr>
<td>WFQ</td>
<td>Weighted Fair Queuing</td>
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<tr>
<td>WSO</td>
<td>Wavelength Searching Order</td>
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Summary

Optical burst switching (OBS) is a promising candidate technology for the next-generation of wavelength division multiplexed backbone transport networks. It is reasonable to assume non-full wavelength conversion capability in practical OBS networks since all-optical tunable wavelength converters (TWCs/WCs) are expensive and still immature technologically. Without full wavelength conversion capability to resolve contentions among bursts for output wavelengths, quality of service (QoS) enhancement intended to reduce burst loss becomes important. In this thesis, we present several QoS enhancement algorithms in OBS networks without full wavelength conversion capability.

First, we propose an offline wavelength assignment algorithm in non-wavelength-convertible OBS networks where no WC is deployed at the core nodes. The key idea is to set the wavelength searching order for each traffic connection at its ingress node based on the wavelength priorities, which are determined using calculated end-to-end burst loss probabilities on the different wavelengths. We also introduce a link model for estimating the burst loss probability on each wavelength. We present simulation results to show that our proposed scheme can significantly reduce the burst loss probability in the network.

Next, we develop an algorithm for allocating WCs at the core nodes to form partially wavelength-convertible OBS networks. We prove this algorithm is optimal in reducing the burst loss probability under the assumption that the traffic loads of connections remain the same along their routes, given the overall number of WCs and the WC deployment structure within the core nodes. The effectiveness of the
Finally, we propose using burst rescheduling to reduce the burst loss probability in a partially wavelength-convertible OBS network. We illustrate that the burst loss due to the unavailability of free WCs can be minimized at a single node using burst rescheduling. Based on this observation and the fact that rescheduled bursts may be dropped at subsequent nodes due to their changed wavelengths, two burst rescheduling algorithms are proposed. The proposed algorithms’ effectiveness in reducing the overall burst loss probability, their computational complexity and their signalling overheads are studied through simulation experiments.
Chapter 1

Introduction

Increasing bandwidth demand is challenging the capacity limits of current backbone transport networks with the number of Internet users increasing dramatically along with various bandwidth-intensive applications (e.g. video conferencing and video-on-demand) emerging to satisfy users’ needs. Currently, wavelength division multiplexing (WDM) is the main candidate transmission technology for the next-generation of networks to meet this demand. A WDM optical fibre can support tens to hundreds of wavelengths, each capable of supporting tens of Gigabits per second or more of data [1].

The Internet Protocol (IP) will continue to play a dominant role [2]. IP-over-WDM is considered more promising compared to other choices, including IP-over-ATM-over-SONET-over-WDM and IP-over-SONET-over-WDM, since it avoids the overhead and complexity associated with encapsulating IP packets at intermediate layers. Therefore, the next-generation of optical networking technology should support the direct transport of IP traffic in the optical layer while making efficient use of the raw bandwidth provided by the WDM links.
Chapter 1. Introduction

1.1 The Emergence Of OBS Technology

Optical burst switching (OBS) was first proposed in 1997 as a candidate all-optical switching technology to support the direct transport of IP traffic in the optical layer in WDM networks [3]. Its details are presented in [4][5][6][7]. The motivation of OBS is to combine the advantages of two counterpart technologies, viz., optical circuit switching (OCS) and optical packet switching (OPS), while avoiding their shortcomings [5].

In OCS (or wavelength routing) networks, bandwidth is managed at the wavelength level to provide lightpaths to IP connections between their source-destination node pairs. A lightpath consists of a dedicated wavelength on each link along a physical route between a node pair. It can be set up dynamically or statically using a two-way reservation process. At the start (source) node of a lightpath, IP traffic undergoes electrical/optical (E/O) conversion to be carried by an optical signal; at intermediate nodes, switch fabrics, i.e., optical cross-connects (OXCs), are configured during the setup stage of the lightpath and switch the signal all-optically from an input wavelength (i.e., a wavelength on an input link) to an output wavelength (i.e., a wavelength on an output link); at the destination node, optical/electronic (O/E) conversion is carried out to convert the IP traffic back into the electronic domain. An IP connection can be routed via more than one lightpath, depending on whether a lightpath exists between its source-destination node pair.

OCS has significant advantages over point-to-point switching technology which is adopted in current backbone networks. In point-to-point switching networks, optical signals carrying IP traffic undergo O/E/O conversion at every node between source and destination nodes. In OCS, however, O/E/O conversion is replaced by all-optical switching at the intermediate nodes of lightpaths. As a result, the burden of electronic processing is reduced, thus leading to a higher data transmission rate as the electronic processing speed is much lower than the optical transmission rate.
However, OCS has several shortcomings. First, it is impossible to allocate one single lightpath for each connection (even after some low-speed connections are combined as higher-speed ones, which is known as traffic grooming [8]), given the limited number of available wavelengths. Therefore, some connections must take multiple lightpaths, undergoing O/E/O conversion at each node connecting two lightpaths on their routes. This will increase network resource consumption and the end-to-end delay. Second, managing bandwidth at wavelength level does not allow the statistical sharing of bandwidth on a wavelength among multiple connections, leading to inefficient use of bandwidth. Third, the extremely high degree of transparency of the lightpaths, i.e., without any electronic processing at the immediate nodes of lightpaths, limits the network management capabilities such as traffic monitoring and fast fault recovery [7].

OPS is proposed to handle the bandwidth at the sub-wavelength level to improve wavelength utilization efficiency. In an OPS network, a packet is sent along with its header (i.e., a control packet) into the network without prior reservation. Upon reaching a node, the header is extracted to be processed electronically while the packet is buffered in the optical domain. Based on the information extracted from the header, the packet is optically switched onto a free output wavelength or dropped if output wavelengths are all busy. This way, bandwidth on a wavelength can be statistically shared among packets from multiple connections. At the same time, some network management capabilities are allowed since headers are processed in the electronic domain at each node.

However, the implementation of OPS is much harder than OCS due to technological constraints. For instance, there is currently no optical random access memory cheap enough to buffer packets while their headers are processed. Instead, they are sent to a length of fibre, i.e., a fibre delay line (FDL), to be delayed. However, FDLs are not fully functional memory since the retrieving of packets is not allowed until they appear at the end of the fibers. FDLs are also bulky in floor space even to provide a very limited delay. For example, about 200m of fibre is required for just 1μs of delay [8]. Besides, other technologies, such as fast optical switching and
the extraction of headers from optical packets, are still in the relatively primitive stage.

In view of the advantages and disadvantages of OCS and OPS, OBS is proposed as a more technologically-practical paradigm to manage the bandwidth at the sub-wavelength level. In OBS, multiple packets are assembled into a burst as the basic transport unit, thus lowering the switching frequency needed. Meanwhile, out-of-band signalling protocol is adopted, i.e., headers of bursts are transmitted on a dedicated control wavelength channel. This way, the extraction of headers is avoided. In addition, headers are separated from data bursts temporally since a burst lags behind its header by an offset time. In doing so, a burst’s header is processed before the burst arrives at a node, which makes it possible to bypass the need for optical buffers. In summary, OBS can work with optical technology constraints while exploiting the attractive properties of optical communications.

1.2 OBS Architecture

![Figure 1.1: An OBS network](image)

Fig. 1.1 shows an OBS network. It consists of a collection of nodes connected by WDM links. A node can function as a core node, an edge node or both at the
same time. At the core nodes, bursts are switched in the optical domain from input wavelengths to output wavelengths. A core node with two input links and two output links\(^1\) is depicted in Fig. 1.2 [2]. Each link carries three wavelengths \(w_0\), \(w_1\) and \(w_2\), with wavelength \(w_0\) being a control wavelength dedicated for headers. The remaining wavelengths are data wavelengths used for burst communication\(^2\).

An aggregate message received at an input link is first demultiplexed by a demultiplexer into different messages, each on a different wavelength. For each of the control wavelengths, an input module (IM) and an output module (OM) are used. A header on a control wavelength is first converted into electronic form by the IM and then the control information carried by the header is extracted. Based on the control information, the next outgoing link for the corresponding burst is determined by consulting a routing table. The header is then buffered until it is scheduled by the scheduler for transmission onto the selected outgoing link. The transmission of the header is carried out by an optical transmitter after the header is forwarded to the OM. Before the header’s transmission, the OM needs to update the control information within the header. The messages on data wavelengths are sent to the optical switch network. Bursts within these messages are switched to

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\(^1\)Unless otherwise stated, there is only one fiber within a link.

\(^2\)Unless otherwise stated, a wavelength refers to a data wavelength.
wavelengths on output links after the optical switch network is re-configured for each burst by the scheduler based on the control information extracted from the headers. Finally, messages destined for an output link are multiplexed by a multiplexer. For each burst, it can be delayed using a fiber delay line and its wavelength can be converted using a wavelength converter, which will be explained in detail in Section 1.3.

The edge nodes are the ingress nodes of IP traffic. They accept IP traffic from access networks, store them in the electronic buffers, assemble IP packets into bursts and implement E/O conversion to send bursts as optical signals. The edge nodes are also the egress nodes of IP traffic. They carry out O/E conversion to convert bursts back into the electronic domain, dissemble bursts to get IP packets and send these packets to the access networks.

Within an OBS network, the routes for connections between ingress-egress (i.e., source-destination) node pairs are usually determined using explicit routing method. In such an approach, routes for connections are determined before bursts belonging to them are transmitted. With explicit routing, a label switching framework such as multi-protocol label switching (MPLS) can be adopted [6][10]. In
MPLS, the route for a connection is called a label switching path (LSP). To be forwarded along an LSP, a header carries a short label to represent the forwarding option at the next downstream node. When the header arrives at a node before its destination, its outgoing link can be determined based on the label within it and the old label is replaced with a new one before the header is passed downstream. Such label based forwarding method needs less processing time at each node, which is particularly suitable for the high burst rate in OBS. Besides, traffic engineering, which aims at managing network resources more efficiently, can be realized using the explicit path selection. Due to its advantages, explicit routing is popularly assumed in the literature on OBS.

After a route is set up for a connection, IP packets belonging to this connection can be sent to the network. These IP packets are first buffered at an ingress node. Based on a burst assembly algorithm [11][12][13], packets are assembled into bursts. When a burst is ready for transmission, a header packet is sent to the burst’s egress node on a dedicated control channel. The header is electronically processed along its path. Based on the information extracted from the header, one wavelength is reserved at each node on the route to provide an end-to-end transparent optical path for the burst. If the wavelength reservation fails at a node, the header will not be passed on to downstream nodes and the burst is dropped. The burst is sent into the network after an offset time without waiting for the feedback information of its header, i.e., one-way reservation is adopted for each burst. To guarantee the completion of the processing of its header before the burst arrives at each node, the offset time should be at least \(H\delta\) at the ingress node, where \(H\) is the number of hops along the route of the burst and \(\delta\) is the time to process the header at a node, assuming as in [5] that the processing time of a header is the same at all the nodes\(^3\). The offset time between the burst and its header is reduced to \((H - h)\delta\) after \(h\) hops. Figure 1.3 illustrates this process [18].

The reservation length on a wavelength on an output link for a burst is de-

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\(^3\)The switch network at a core node needs to be configured upon the arrival of a burst. For simplicity, the time to configure the switch fabric is counted into \(\delta\).
terminated by the signalling protocol adopted in an OBS network. With the Just-In-Time (JIT) protocol [14], a wavelength is reserved immediately after a header is processed and released after a release message is received. With the Horizon scheme [15], a reservation still starts after the processing of a header but is released by the end of the burst. With the Just-Enough-Time (JET) protocol [5], a wavelength is reserved for a burst only for its duration. The latter two schemes need the offset time and burst length information to be included in a header. An example of the reservations for a burst on a wavelength with JIT, the Horizon scheme and JET is shown in Fig. 1.4. It can be seen that the bandwidth during the period from the time the processing of a header is finished to the arrival time of the corresponding burst needs to be reserved with JIT and the Horizon scheme but not with JET. Besides, the reservation with JIT for a burst ends later than those with JET and the Horizon scheme due to its open-ended wavelength reservation mechanism. Comparatively, bandwidth can be best utilized with JET, which has become the most dominant signalling protocol\(^4\).

Besides the above-mentioned version of OBS with one-way reservation for each burst, some researchers have also proposed a centralized version of OBS with two-way reservation [17]. In such an OBS network, a reservation message is sent to a centralized server before a burst is transmitted. The burst is sent only after

\[^4\]Detailed comparison between JET, JIT and the Horizon scheme can be found in [16].
a feedback message is received from the server telling that wavelengths along its route have been successfully reserved. In doing so, the transmission of bursts is guaranteed. However, two-way reservation for each burst introduces long delay and the centralized nature of this scheme does not scale well in long-haul backbone networks.

1.3 Quality Of Service In OBS Networks

Quality of service (QoS) in OBS networks is mainly evaluated on the burst loss probability due to the bufferless nature of OBS. Although FDLs can be deployed at the core nodes, they are not fully functional buffers and can only provide very limited delay. Therefore, when a burst cannot be allocated onto an output link, it is usually dropped. Meanwhile, without buffers at the core nodes, the latency experienced by a burst mainly includes the total processing time for its header and the propagation delay along its route. Therefore, latency can be relatively well determined. With the burst loss performance as the main QoS metric, the aims of QoS mechanisms in OBS networks can be broadly divided into two categories: QoS provisioning and QoS enhancement [18].

QoS provisioning aims to provide acceptable end-to-end services for various applications, as perceived by the end users. QoS provisioning is important for end users since it allows them to specify their service requirements and pay accordingly. Besides, some applications (e.g. video conferencing and online gaming) have more stringent operating requirements than other applications (e.g. email and web browsing). QoS provisioning can be realized in either a relative or an absolute way. With a relative QoS provisioning mechanism, some traffic classes perform relatively better than other classes but there is no quantitative guarantee for the performance of the traffic classes. By contrast, an absolute mechanism can guarantee the worst-case end-to-end burst loss probability of each connection. Although absolute mechanisms are desirable, relative mechanisms are useful in
complex network scenarios where it is difficult to provide quantitative guarantees. Different QoS provisioning approaches will be reviewed in Chapter 2.

QoS enhancement refers to improving the general performance of the network [18]. In doing so, more users can be serviced, given their QoS requirements and a fixed amount of network resources. This is desirable for both the end users and network operators. For users, they get better services after network performance is improved given the overall number of users. Besides, they have a higher probability to be serviced. For the network operators, they are capable of attracting more customers and hence making more profit out of their investments. QoS can be enhanced using software methods and hardware methods. Software methods include various algorithms for QoS improvement, which will be reviewed in Chapter 2.

Hardware methods include, for instance, deploying FDLs and tunable all-optical wavelength converters (TWCs/WCs) at the core nodes. An FDL, as explained before, is a length of fibre to delay bursts. An all-optical WC is used to change an input wavelength to another wavelength without O/E/O conversion, thus not increasing the burden of electronic processing and not decreasing the data transmission rate in OBS networks. There are multiple ways of achieving all-optical wavelength conversion [8]. An example of using FDLs and WCs to reduce the burst loss probability is shown in Fig. 1.5. Burst 1 has been allocated onto wavelength 1 on the output link when burst 2 arrives on wavelength 1 on an input link. If there is neither WC nor FDL, burst 2 has to be dropped since it overlaps
with burst 1. Using an FDL, however, it can be accepted on wavelength 1 after it is delayed. Using a WC, it can be allocated onto wavelength 2 after its wavelength is changed.

FDLs, however, are not fully functional buffers and cannot provide random access ability. Besides, they are bulky even to provide a very short delay on the order of microseconds (some works on reducing the floor space occupied by FDLs can be found in [19][20][21][22]). Therefore, they are considered to be scarce resources and often assumed to be absent. Relatively, WCs are considered to be more important since they allow the bandwidth on a wavelength to be stochastically shared by bursts from different wavelengths, leading to higher bandwidth utilization efficiency and a lower burst loss probability.

1.4 Wavelength Conversion In OBS Networks

![Dedicated wavelength converter deployment structure](image)

Figure 1.6: Dedicated wavelength converter deployment structure

The capability of wavelength conversion in OBS networks depends on the type and deployment structure of WCs within the core nodes. WCs can be either limited-ranged (LWCs) or full-ranged (FWCs). An LWC can convert the input wavelength to a subset range of wavelengths in the vicinity of the input wavelength, while an FWC can convert to any wavelength [2]. WCs can be deployed at a core...
node using three basic structures, viz., dedicated, share-per-node (SPN) and share-per-link (SPL). Other WC deployment architectures can be designed based on these three structures (e.g. the architectures used in the case of multiple fibers per link and the architecture proposed in [23]).

The dedicated WC deployment structure is depicted in Fig. 1.6. There are multiple input/output links, each with \( W \) different wavelengths. There is one dedicated WC for each wavelength on each output link. With dedicated WC deployment structure, no burst will be dropped due to the lack of free WCs to convert it to a free output wavelength, which is desirable for QoS improvement. However, WCs (especially FWCs) are expensive. With network operators intending to make more profit out of their investments, the cost on WCs needs to be well controlled. Meanwhile, all-optical WCs are still immature technologically. These facts become the motivations for the SPN and SPL structures, which can reduce the number of WCs needed within the core nodes to reach or approach a required burst loss performance.

The SPN WC deployment structure is shown in Fig. 1.7. Within such a structure, a dedicated WC bank (WCB) consisting of multiple WCs (\( C \) in Fig.
1.7) is deployed for the node. If a message from a demultiplexer does not require conversion, it is directly switched to a multiplexer. Otherwise, it is fed into the WCB and later sent back to the switch to be switched to a multiplexer. The SPL WC deployment structure is depicted in Fig. 1.8, where one dedicated WCB is deployed for one output link. In both structures, the ratio of the number of WCs within a WC bank to the number of related output wavelengths, i.e., those from a node in the share-per-node structure and on a link in the share-per-link structure, is called the conversion ratio in this thesis.

These three structures have different WC sharing efficiency and switching complexity. WC sharing efficiency can be evaluated using the number of output wavelengths related to a WC, which equals the reciprocal of the conversion ratio in the SPL and SPN structures. The larger the WC sharing efficiency, the better a WC can be stochastically shared by bursts from different wavelengths. The increasing order of the three structures’ WC sharing efficiency is: dedicated, SPL and SPN, given a burst loss performance threshold in the case of SPL or SPN structure. This order is the same with the decreasing order of the three structures’ costs on WCs, since the more efficiently WCs are shared, the fewer WCs are needed to achieve or approach a required burst loss performance. The switching complexity of a WC deployment structure can be evaluated using the number of ports of its switch.
The increasing order of the three structures’ switching complexity is: dedicated, SPL and SPN, since their switching complexity is $NW \times NW$, $NW \times (NW + C_a)$ and $(NW + C_a) \times (NW + C_a)$, respectively, where $C_a$ is the total number of WCs deployed within a node with SPL or SPN structure and $N$ is the number of input/output links. The higher the switching complexity, the more costly a switch. Currently, field-tested and qualified large-port-count optical switches are still in the distant future [1].

An OBS network has full wavelength conversion capability if each node within it uses 1) dedicated WC deployment structure with FWCs, or, 2) a WC sharing deployment structure with FWCs and the conversion ratio being one. Otherwise, an OBS network has non-full wavelength conversion capability. Particularly, if no WC is used, an OBS network has no conversion capability; otherwise, it has partial wavelength conversion capability with limited conversion range of WCs and/or limited number of WCs.

### 1.5 Motivation And Contributions

A majority of works on OBS assume full wavelength conversion capability. However, all-optical WCs are expensive and technologically immature currently. Therefore, non-full wavelength conversion assumption is more reasonable and is receiving more and more attention in recent literature [24][25][26][27][28]. Besides, such assumption is in line with the motivation of OBS to be practical by fully considering optical technology constraints. Without full wavelength conversion capability to resolve contentions among bursts for output wavelengths, QoS enhancement becomes even more important.

In this thesis, we focus on three issues related to QoS enhancement in OBS networks with non-full wavelength conversion capability. These issues include 1) wavelength assignment in non-wavelength-convertible OBS networks, 2) allocation optimization of a given number of WCs at the core nodes to form a par-
tially wavelength-convertible OBS network, and 3) burst scheduling in a partially wavelength-convertible OBS network. We study these issues under the assumption of JET and explicit routing due to their popularity.

1.5.1 Wavelength Assignment

Wavelength assignment aims to order the wavelength IDs to form a wavelength searching order (WSO) for each connection at its ingress node. It is an important method to reduce the burst loss probability in non-wavelength-convertible OBS networks. In this thesis, we develop a priority-based offline wavelength assignment scheme. The key idea of the scheme is to generate the WSO of each traffic connection according to the wavelength priorities, which are determined based on calculated end-to-end burst loss probabilities on different wavelengths. Compared to existing schemes, our proposed scheme can make use of any possible WSOs instead of only a small subset of WSOs. This is attractive since a limitation on the choice of WSOs will decrease the performance of wavelength assignment. Besides, our scheme is based on a more accurate link model for estimating the burst loss probability on each wavelength. Our simulation results indicate that the proposed scheme can reduce the network-wide burst loss probability significantly compared with other schemes. It is also illustrated that the performance of the proposed scheme can be further enhanced by a larger number of wavelengths per link and a reasonable delay bound at the edge nodes.

1.5.2 Wavelength Converter Allocation

Given the overall number of WCs and the WC deployment structure within the core nodes, the best QoS performance can be obtained when WCs are optimally allocated. The WC allocation problem has been extensively studied in the literature on OCS [29][30][31][32]. However, OBS and OCS are different paradigms using different QoS metrics (with burst loss probability in OBS and connection
rejection probability in OCS). To the best of our knowledge, in the literature there is no work on WC allocation in OBS networks. In this thesis, we propose a WC allocation algorithm and prove that it is optimal under the assumption that traffic loads of connections remain the same along their routes. The effectiveness of the algorithm is verified through simulation results.

1.5.3 Burst Scheduling

Upon the arrival of a header, the corresponding burst should be scheduled onto an output wavelength. One important aim of a burst scheduling algorithm is to decrease the burst loss probability. However, a majority of algorithms in the literature are proposed under full wavelength conversion assumption. They do not consider the burst loss due to insufficient WCs, i.e., bursts dropped due to the unavailability of free WCs to convert them onto unused wavelengths, which exists in a partially wavelength-convertible network with limited number of WCs. Earlier research works have shown that reducing the burst loss due to insufficient WCs is key to decreasing the overall burst loss probability. In this thesis, we demonstrate how to use burst rescheduling to decrease the burst loss due to insufficient WCs and hence cut down on the overall burst loss probability in OBS networks. Two burst rescheduling algorithms are proposed. Their effectiveness in reducing the overall burst loss probability, their computational complexity and their signalling overheads are studied through simulation experiments.

1.6 Outline Of The Thesis

The thesis has six chapters. This chapter has introduced OBS and the motivation of our works in this thesis. Chapter 2 gives a survey of the existing QoS mechanisms in OBS, including different algorithms for QoS enhancement and various approaches for QoS provisioning. Since most of these methods are proposed under full wavelength conversion assumption, their effectiveness in non-fully wavelength-
convertible OBS networks is examined. Chapter 3 presents the priority-based off-line wavelength assignment in non-wavelength-convertible OBS networks. Chapter 4 introduces the WC allocation algorithm. Burst rescheduling is discussed in detail in Chapter 5. We summarize our research work and discuss possible future extensions in Chapter 6.
Chapter 2

QoS In OBS Networks: An Overview

QoS mechanisms in OBS networks are intended to realize QoS provisioning and QoS enhancement with the burst loss probability as the main QoS metric. QoS enhancement refers to improving the general performance of the network. It can be realized using software mechanisms (i.e., various algorithms) and hardware methods (e.g. deploying FDLs and WCs at the core nodes). QoS provisioning aims to provide acceptable end-to-end services for traffic connections. Particularly, an absolute QoS provisioning mechanism can provide a quantitative guarantee for the worst-case QoS performance of each connection and a relative mechanism only controls the relative performance of connections based on their traffic classes. Although the focus of this thesis is on QoS enhancement mechanisms, we survey both QoS enhancement algorithms\(^1\) and QoS provisioning mechanisms in this chapter. This is because, while a QoS provisioning mechanism may affect the burst loss performance in the network, the burst loss requirement of a connection also may be considered in a QoS enhancement mechanism (e.g. traffic engineering). Most of the approaches surveyed in this chapter are proposed under the full wavelength

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\(^1\) These are software QoS enhancement mechanisms. An introduction of the hardware QoS enhancement mechanisms can be found in Section 1.3 of Chapter 1.
conversion assumption. Therefore, we will examine their effectiveness in non-fully wavelength-convertible OBS networks when presenting them.

2.1 QoS Enhancement

QoS enhancement mechanisms in OBS networks broadly include burst scheduling, WC allocation optimization, deflection routing, wavelength assignment, traffic engineering and burst overlap reduction. Particularly, the latter three are intended to improve the burst loss performance by reducing contentions at the core nodes. Contention occurs when multiple bursts overlapping with each other and destined for the same output link arrive on the same wavelength on different input links. In this case, bursts may be dropped due to 1) the unavailability of free WCs to convert them to unused wavelengths within the conversion range of WCs (we call this kind of burst loss WC-induced burst loss in this thesis) and 2) the unavailability of unused wavelengths within the conversion range of WCs (i.e., non-WC-induced burst loss). Obviously, in fully wavelength-convertible OBS networks, only non-WC-induced burst loss exists. Or, more accurately, burst loss arises only when the number of bursts arriving simultaneously is larger than the number of wavelengths per link.

In this section, we present some schemes for burst scheduling, wavelength assignment, traffic engineering, deflection routing and burst overlap reduction. The WC allocation problem is not discussed in this section since, to the best of our knowledge, there is no work on it in the literature on OBS. An introduction to this problem can be found in Section 1.5.2 of Chapter 1.

2.1.1 Burst Scheduling

Upon the arrival of a header, the corresponding burst should be scheduled onto an output wavelength. An efficient burst scheduling algorithm can improve the
A majority of burst scheduling algorithms are proposed assuming full wavelength conversion where there is no WC-induced burst loss. These algorithms aim to reduce non-WC-induced burst loss by decreasing the bandwidth existing in voids/gaps between reservations for different bursts on each wavelength (e.g. the gap between the reservations for bursts 2 and 3 in Fig. 2.1 and that between bursts 1 and 2 in Fig. 2.2). These voids may overlap with incoming bursts (e.g. new bursts in Figs. 2.1 and 2.2) since the arrival order of bursts is different from that of their headers due to the different offset times of the bursts. However, there is no guarantee that these voids can be used to accommodate other bursts, thus

bandwidth utilization efficiency and thus decrease the burst loss network-wide, including the non-WC-induced and the WC-induced burst loss.
leading to wasted bandwidth within voids and higher non-WC-induced burst loss. To decrease the bandwidth wastage within the voids, some algorithms try to make reservations for bursts in the order of their arrival times instead of their headers’ arrival times [43][44][45]. Particularly, the ordered scheduling (OS) algorithm fully realizes such an idea [45]. Other algorithms try to enhance the performance of the latest available unused channel (LAUC) algorithm using one or multiple methods such as void-filing [7][15][41] and rescheduling [56]. Under the assumption of non-full wavelength conversion, the conversion avoidance scheduling (CAS) algorithm is proposed in [46]. For all these algorithms proposed under different assumptions of wavelength conversion capability, burst segmentation can be used to enhance their performance since it allows a segment of a burst to be allocated when the burst fails to be accommodated as a whole [51][52][53][54]. In this section, we present OS, CAS, LAUC and its variants using void filling, burst rescheduling and segmentation as representative algorithms.

2.1.1.1 OS

In this approach, the scheduling of a burst consists of two phases. In the first phase, when a header packet arrives at a node, an admission control test is carried out to determine whether there is enough bandwidth to accommodate the corresponding burst on the outgoing link. If the burst fails the test, it is dropped. Otherwise, the related reservation information like the start time and length of the burst is stored electronically and the header is passed on to the next node. The second phase begins just before the burst’s arrival time to determine a wavelength on the outgoing link for the burst. Since the burst has passed the admission control test, it is ensured that a free wavelength can be found for the burst based on the stored information related to it. After the second phase, a NOTIFY packet is immediately sent to the next node to inform it of the wavelength of the burst. Since reservations for bursts can be made in the order of their start time, no burst that passes the admission control test will overlap with existing voids and the bandwidth wasted in voids is minimized. In this sense, OS is optimal. The computational complexity of
the OS algorithm depends on the implementation method of the admission control test and is relatively high compared with algorithms presented later. OS cannot be implemented in OBS networks with non-full wavelength conversion capability since the admission control test is designed under the assumption of full wavelength conversion.

2.1.1.2 LAUC

LAUC is also known as Horizon in [15]. This algorithm needs to keep track of the end time of the last scheduled burst, i.e., unscheduled time, on each wavelength. When a header arrives, the unscheduled time at every wavelength is examined and the burst is allocated onto the wavelength with the latest unscheduled time before its arrival time (e.g. by LAUC the new burst in Fig. 2.1 is scheduled to the third wavelength). In doing so, the void formed between a new burst and the burst before it on the same wavelength is reduced. After the burst is scheduled on a wavelength, the unscheduled time of the wavelength is updated. The computational complexity of this algorithm is $O(W)$ using a linear search method, where $W$ is the number of wavelengths.

2.1.1.3 LAUC With Void Filling

In scheduling using LAUC with void filling (LAUC-VF), both the unscheduled time and voids on each wavelength are kept track of and bursts can be filled into voids (e.g. by LAUC-VF the new burst is filled into the void between bursts 2 and 3 in Fig. 2.1). Since the bandwidth within voids can be utilized, LAUC-VF improves the burst loss performance. LAUC-VF has several variants. In [7], a wavelength is chosen such that the void between the new burst and the burst before it is minimized. In [41], it is considered that bandwidth within voids has a higher probability to be wasted than the bandwidth after the unscheduled time. Therefore, priority is given to wavelengths with voids. In [42], voids generated before and after a new burst are both considered. The computational complexity
of LAUC-VF is $O(WV)$ with a linear search method, where $W$ is the number of wavelengths per link and $V$ is the maximum number of voids on a wavelength.

### 2.1.1.4 LAUC With Burst Rescheduling

In this approach, bursts allocated already can be rescheduled to other wavelengths to improve the bandwidth utilization efficiency. For each burst being rescheduled, a NOTIFY packet needs to be sent immediately to the next node to inform it of the new wavelength. Reference [56] studies the single-level burst rescheduling in detail. With single-level burst rescheduling, only one burst can be rescheduled to accommodate a new burst, which is attractive due to its lower computational complexity compared with the choice of rescheduling multiple bursts simultaneously.

Fig. 2.2 gives an example of single-level burst rescheduling, where a new burst is accepted after burst 1 is rescheduled from wavelength 1 to wavelength 2. Two burst rescheduling algorithms are proposed in [56]. In the on-demand burst rescheduling (ODBR) algorithm, rescheduling is considered only when LAUC fails to allocate a burst. In the aggressive burst rescheduling (ABR) algorithm, rescheduling is carried out if it can reduce the length of voids. The two algorithms lie in between LAUC and LAUC-VF in terms of computational complexity and burst loss performance.

### 2.1.1.5 LAUC With Segmentation

Since a burst is composed of multiple IP packets, it can be segmented at the position between two packets. This way, part of a burst can be scheduled while the remaining part is dropped when the burst fails to be scheduled as a whole. An example is shown in Fig. 2.2, where the tail end part of a new burst is dropped and its head end part is allocated to wavelength 3. After a burst is segmented, a NOTIFY packet should be generated to inform the next node about the change. LAUC with burst segmentation has several variants. In the head-dropping variant [51], only the head end part of a burst can be dropped. In the tail-dropping variant [52], the dropped segment is the tail end part of a burst. comparatively,
the tail-dropping variant will cause less out-of-order problem for packets at their destinations. In another variant [55], both the tail end and head end parts of a burst can be dropped in pursuit of the highest throughput. In all these variants, additional segment headers are needed for the segments inside a burst.

2.1.1.6 CAS

The aforementioned algorithms have been proposed under the full wavelength conversion assumption. They are not suitable for being used directly in partially wavelength-convertible OBS networks with non-zero WC-induced burst loss. The reason is that they may use WCs to allocate bursts to other wavelengths when their original wavelengths, i.e., the wavelengths they are from, are free so as to reduce non-WC-induced burst loss, which will dramatically increase WC-induced burst loss [46]. On the contrary, in the CAS algorithm, a burst will be allocated to its original wavelength if it is free. Otherwise, the LAUC-VF algorithm is invoked to schedule the burst onto another wavelength. Compared with the original LAUC-VF algorithm, fewer WCs are used by scheduled bursts and hence less incoming bursts are dropped due to the unavailability of free WCs. However, non-WC-induced burst loss with CAS is higher than that with LAUC-VF since original wavelengths of bursts may not be the best ones to reduce the non-WC-induced burst loss. Nevertheless, simulation results show that the CAS algorithm can significantly decrease the overall burst loss probability in most situations. This phenomenon indicates that reducing WC-induced burst loss is key to lowering the overall burst loss when the number of WCs is not large enough to provide full wavelength conversion capability.

2.1.2 Wavelength Assignment

The objective of wavelength assignment is to order the wavelength IDs to form a WSO for each connection at its ingress node. A burst belonging to a connection will search wavelengths sequentially according to the connection’s WSO at its
ingress node for available resources. As soon as a wavelength is found to be free within a delay bound, the burst will be delayed appropriately and sent out on that wavelength\(^2\). Adjusting the WSO of a connection can affect the throughput of the connection on different wavelengths at its ingress node, thus changing the burst contention situation on each wavelength at the core nodes along the connection’s route. Therefore, by adjusting the WSOs, it is possible to decrease the burst loss probability in OBS networks with non-full wavelength conversion capability. Wavelength assignment schemes can be realized either online or offline \([24]\ [26]\ [27]\ [28]\). Relatively, an offline scheme is carried out on a long term basis to optimize the system performance.

Traditional wavelength assignment approaches do not consider the traffic load information and burst contention situation in the network and can be implemented either online or offline. One such scheme is first fit (FF), where wavelengths are searched in an increasing order according to their IDs. Therefore, all connections have the same WSO. Meanwhile, if wavelength assignment is not limited to setting WSOs for connections, traditional schemes also include the random scheme \([24]\), in which one of the free wavelengths is randomly chosen for a burst. In general, not being based on the traffic load information, traditional schemes are inefficient in reducing the burst loss probability, as has been verified by simulation results in recent papers \([24]\ [26]\ [27]\ [28]\).

Priority-based wavelength assignment (PWA) is an online wavelength assignment scheme considering the contention situation in the network \([26]\). It is proposed for non-wavelength-convertible OBS networks. In this approach, the burst dropping probabilities of a connection on different wavelengths are continually fed back to the connection’s ingress node. Based on this information, the WSO for the connection is updated periodically as the decreasing order of the wavelengths’ priorities: the lower the burst loss probability on a wavelength, the less likely bursts transmitted on the wavelength are to be dropped, thus the higher the priority of the

\(^2\)Since wavelength assignment schemes and burst overlap reduction algorithms only affect burst scheduling at the edge nodes, we do not categorize them as burst scheduling algorithms.
wavelength. Simulation results show PWA can dramatically reduce the burst loss probability compared with FF and the random scheme. In [27], PWA is modified to be used in OBS networks with partial wavelength conversion capability.

The problem of offline wavelength assignment considering the traffic load information is only studied in non-wavelength-convertible OBS networks currently. With the objective to minimize the burst loss probability, it is a NP-complete problem since its special case of finding the WSO for a single connection is in fact a travelling salesman problem [79] when each wavelength is considered as a city. In [28], many approximations are made to relax the optimization formulation of the problem. These approximations decrease the scheme’s performance to the extent that it performs worse than the heuristic scheme proposed in [24]. This heuristic scheme sets one WSO for all connections originating from an ingress node. Simulation results show that it can significantly improve the burst loss performance compared with other offline schemes. Its main disadvantage is that it can only use a very small subset of WSOs, which limits its performance dramatically.

2.1.3 Traffic Engineering

The purpose of traffic engineering is to map traffic onto the physical topology by determining routes for connections. In OBS networks, traffic engineering is utilized to reduce the burst loss probability and can be realized either online or offline. Existing online algorithms in the literature assume multiple candidate paths are predetermined for each node pair. These paths are relatively short to reduce the network resources consumed by connections. In [34][35][36], different methods are proposed to adjust periodically the proportion of traffic transmitted along the candidate paths between a node pair based on the feedback information about the burst loss probabilities on these paths. In [37][38], approaches are presented to choose one path for a connection from the candidate ones which can meet the connection’s QoS requirements. This decision is made upon the connection’s arrival and will not change later. Offline traffic engineering can be formulated as an
optimization problem with its objective being to minimize the calculated burst loss probability. With different link models for estimating the burst loss probability on a link, connections will be routed differently [39][40]. Existing online and offline traffic engineering algorithms can be carried out in OBS networks with different wavelength conversion capabilities. Particularly, if a link model is used in an algorithm, it needs to be adjusted based on the wavelength conversion assumption (this applies in the sequel when we say an approach can work under different wavelength conversion assumptions).

2.1.4 Deflection Routing

Deflection routing allows a burst to take another route different from the pre-determined one when it fails to be scheduled at a node. The alternative route for a deflected burst at a node can be pre-specified [47] or dynamically decided based on the contention situation on different links [48][49][50]. The main problem with deflection routing is that the alternative route for a deflected burst may be longer than its original one. This will cause a header to be overtaken by its burst and fail to make the proper resource reservations. To resolve this problem, extra offset time can be introduced at the edge nodes or FDLs are deployed at the core nodes to delay deflected bursts [47]. Meanwhile, longer alternative paths also lead to increased network resource consumption, which tends to decrease the burst loss performance in the network. For this problem, some threshold check functions are introduced in [48] to assist in making a choice between dropping a burst and deflecting it when it fails to be scheduled at a node. The implementation of deflection routing is independent of wavelength conversion assumptions.

Though deflection routing schemes affect the scheduling of bursts, we do not categorize them as burst scheduling algorithms. The reason is that they do not determine which wavelength a burst should be allocated onto.
2.1.5 Burst Overlap Reduction

The purpose of burst overlap reduction is to reduce burst overlapping degree, i.e., the number of bursts arriving simultaneously on an outgoing link. When the overlapping degree exceeds the number of wavelengths on a link, some bursts must be dropped. The larger the overlapping degree, the higher the burst loss on the link. In [33], the burst overlap reduction algorithm (BORA) is proposed. In this algorithm, a delay bound is introduced at the ingress nodes, with which bursts belonging to a connection can be allocated to as few wavelengths as possible. This way, overlapping degree of bursts within each connection and hence the overall overlapping degree at downstream nodes is reduced. This algorithm is not suitable for OBS networks without full wavelength conversion capability. The reason is that BORA may have all traffic concentrating to a few wavelengths, which will cause serious contentions for these wavelengths at the core nodes and hence excessive need for WCs to convert bursts from their original wavelengths, leading to higher WC-induced burst loss probability and thus larger overall burst loss probability.

2.2 Relative QoS Provisioning

With relative QoS provisioning, there is no quantitative guarantee for the QoS performance of traffic classes. Instead, it is only required that the QoS performance of a high priority class is better than that of a lower priority class. Particularly, the proportional QoS provisioning model aims at providing a clearer control on the relative performance of traffic classes [60]. In such a model, each traffic class is associated with a differentiation factor. The focus is to make sure the ratio of the burst loss probabilities of different classes obeys the predetermined ratio of the class differentiation factors. If the performance of a high priority class is independent of the traffic load of all lower priority traffic, classes are 100% or completely isolated. Otherwise, they are partially isolated (e.g., in the proportional QoS model). The majority of existing relative QoS provisioning schemes fall into
one of the following four categories. In general, these schemes can be carried out under different wavelength conversion assumptions.

2.2.1 Intentional-Dropping Based Service Differentiation

This approach allows the dropping of a burst even when there are resources to accommodate the burst. By making lower priority bursts more likely to be chosen and intentionally dropped, services are differentiated. In [60], this method is utilized to realize proportional service differentiation. When the predefined ratio of two classes’ differentiation parameters is violated, bursts from the lower priority class are intentionally dropped. In [61], each class is related to a delay bound at the edge nodes. The lower the priority of a class, the shorter the delay bound. When a burst is delayed beyond the delay bound set for its class, it is intentional dropped. In [62], when the average queue length at an edge node exceeds a given threshold, an incoming burst is dropped with a probability. A class with a higher priority is set with a smaller probability. In [61] and [63], intentional dropping occurs when the number of FDLs [61] or bandwidth [63] occupied by bursts from a class exceeds a predefined threshold. The main disadvantage of intentional dropping is that it may unnecessarily drop bursts that otherwise would be accepted, thus leading to lower bandwidth utilization and larger burst loss probability.

2.2.2 Preemption-Based Service Differentiation

This approach allows a high priority burst to preempt a lower priority burst when it fails to be scheduled. In [64][65], preemption is carried out with different bandwidth quotas being set for different traffic classes. When a burst from a class consuming less than its bandwidth quota fails to be scheduled, a burst from a class consuming more than its bandwidth quota is preempted. A burst can be preempted completely [64][65] or partially using burst segmentation [65]. The scheme proposed in [66] is also preemption based but without bandwidth quotas being set for traffic classes.
A low priority burst from class $i$ gets preempted completely or partially by a high priority burst from class $j$ with probability $p_{ji}$ and $1 - p_{ji}$, respectively, when the class $j$ burst fails to be scheduled. By tuning $p_{ji}$, proportional loss differentiation can be realized. The main disadvantage of preemption based schemes is that the bandwidth consumed by preempted bursts at downstream nodes is wasted.

2.2.3 Header-Buffering-Based Service Differentiation

Instead of processing a header upon its arrival, this approach delays the scheduling decision for a burst by buffering each header for a certain time. In [67], among the buffered headers, high priority ones are scheduled earlier than lower priority ones. This way, fewer high priority bursts are dropped since they can access resources earlier. In [68], weighted fair queuing (WFQ) scheduling is used at each node. The disadvantage of the header buffering based schemes is that they need a larger offset time at the edge nodes or otherwise FDLs at the core nodes to delay bursts.

2.2.4 Contention-Ability-Based Service Differentiation

With this approach, a traffic property is adjusted at the edge nodes based on the traffic’s class such that high priority bursts’ ability to win contentions at the core nodes is higher than that of lower priority bursts. This way, computational complexity is reduced at the core nodes. The property to be adjusted can be, for instance, the position of IP packets within a burst [57] and the burst offset time [9]. In [57], high priority IP packets are assembled into the segments less likely to be dropped within bursts. For instance, if the tail-dropping burst segmentation algorithm [51] is implemented at the core nodes, IP packets are sorted in decreasing order of their priorities within each burst.

In the prioritized JET (pJET) protocol, the concept of using offset time to achieve QoS differentiation is proposed [9]. The key idea of pJET is to assign a longer offset time to high priority bursts. This way, high priority bursts’ headers
can arrive earlier to reserve wavelengths with a larger success probability. The pJET protocol is not suitable for providing complete class isolation since this requires unbearable end-to-end delay due to the offset time [9]. The scheme’s burst loss performance is first analyzed in [9], where the upper and lower bounds on the burst loss probability of a traffic class are derived under the ideal assumption of complete class isolation. In the case of partial isolation, detailed performance analysis is presented in [58]. The offset time is later used in [59] to realize end-to-end proportional QoS differentiation, which is achieved by adjusting the offset time assigned for traffic classes at the edge nodes based on the feedback information from the network. The main disadvantage of offset based schemes is that they introduce longer offset times, which increase the end-to-end delay and require larger buffers at the ingress nodes.

2.3 Absolute QoS Provisioning

The purpose of an absolute service differentiation scheme is to guarantee a quantitative upper bound on the end-to-end burst loss performance of each traffic connection. In such a scheme, the end-to-end loss budget, i.e., the maximum acceptable end-to-end loss probability, of a connection is divided into small portions, each allocated to a node along the connection’s route. The allocated burst loss threshold to a node can be only chosen from a limited number of predefined values, each tagged to a local (or per-hop) traffic class. The burst loss threshold of a traffic class at a node is guaranteed using two mechanisms. The first mechanism is link-based admission control which estimates whether the thresholds for the various traffic classes can be preserved at each node along a connection’s route if the connection is accepted. The second mechanism is per-hop absolute QoS differentiation to keep the performance of each local traffic class conforming to its threshold at the node. Similar to the relative QoS provisioning schemes, existing absolute service differentiation schemes can be implemented under different wavelength conversion assumptions.
The end-to-end loss budget can be partitioned in two ways in an absolute service differentiation scheme. Most papers assume equal loss budget partitioning, in which the loss budget is divided into equal parts [69][70]. In [72], unequal loss budget partitioning is proposed. In this approach, upon the arrival of a connection, the lowest burst loss probability or the highest priority that can be provided for the connection at each node is estimated using the link-based admission control. Based on this estimate, a loss budget partitioning decision is made. Compared with equal loss budget partitioning, this method can improve the bandwidth utilization efficiency since links along a route are usually not equally loaded.

The approaches to realize per-hop absolute service differentiation are similar to those listed in Section 2.2 for provisioning relative service differentiation. However, these approaches are designed differently to ensure the burst loss performance of each local traffic class conforms to its threshold. In [69][70], intentional burst dropping based methods are proposed. The burst loss threshold of a traffic class is mapped as the maximum number of wavelengths accessible by bursts from the traffic class. When this limitation set for a traffic class is violated, bursts from the class are dropped. References [71][72] use preemption to realize service differentiation. In [71], the maximum number of accessible wavelengths is still set for a traffic class. But this limitation is dormant until a burst fails to be scheduled and needs to preempt another burst. The scheme in [72] tries to keep the distances to the burst loss thresholds set for different traffic classes equal at a node, thus ensuring no individual connection can breach its threshold and affect those traffic classes that conform to their thresholds. To realize this, a burst from a class with the farthest distance to its threshold is chosen to be preempted when an incoming burst fails to be scheduled.

Link-based admission control methods vary with the per-hop absolute service differentiation schemes. In the service differentiation schemes in [69][70][71], the burst loss threshold for a traffic class is mapped as the maximum number of wavelengths accessible by bursts from the class. Therefore, the link-based admission control is to ensure the total number of wavelengths allocated to traffic classes is
less than the number of wavelengths per link. In [72], the link-based admission control guarantees that the average distance to burst loss thresholds set for the different classes is greater than zero.

2.4 Summary

In this chapter, we have presented a survey of reported QoS enhancement algorithms and QoS provisioning schemes in OBS networks. For schemes proposed under the assumption of full wavelength conversion, we have examined their effectiveness in non-fully wavelength-convertible OBS networks. We have shown that most of them can be used under different wavelength conversion assumptions, with possible adjustments to the link models.
Chapter 3

Priority-Based Offline Wavelength Assignment

3.1 Introduction

Wavelength assignment is an important mechanism to reduce the burst loss probability in OBS networks without wavelength conversion capability. In wavelength assignment, wavelength IDs are ordered to form a wavelength searching order (WSO) for each connection at its ingress node. When a burst belonging to a connection is ready to be sent, wavelengths are searched sequentially according to the connection’s WSO at its ingress node. If a wavelength is found to be free within a delay bound, the burst will be delayed appropriately and sent out on that wavelength. As a result, the throughput of a connection on a wavelength at the connection’s ingress node depends on the position of the wavelength within the connection’s WSO. Since the throughput on wavelengths at the ingress nodes determines the traffic load and hence burst loss on different wavelengths at the core nodes, it is possible to decrease the network-wide burst loss by changing the WSOs of connections (the WSO set). In this thesis, we focus on the offline wavelength assignment problem.
Existing wavelength assignment schemes in OBS networks can be categorized into two groups. The first group consists of the first fit (FF) scheme and the random scheme\(^1\), which do not consider the traffic load situation in the network and have been proven inefficient in reducing the burst loss probability [24]. Wavelength assignment schemes considering the traffic load information belong to the second group called first fit based on traffic engineering (FFTE). Reference [24] proposes a node-based FFTE (NFFTE) scheme which sets one WSO for connections from an ingress node. In the NFFTE scheme, connections’ WSOs are decided based on "inter-node interference". For a pair of ingress nodes, the inter-node interference is the sum of traffic loads of connections originating from them and passing at least one interference link, which refers to a common link traversed by at least two connections each from one of the node pair. As an example, assume connections 1, 2 and 3 originate from ingress node 1 and connections 4, 5 and 6 from ingress node 2. Among these connections, connections 1 and 4 share link 1 and connections 2 and 5 share link 2 along their routes. Therefore, links 1 and 2 are interference links for ingress nodes 1 and 2 and the inter-node interference is the total traffic load of connections 1, 2, 4, and 5. Based on the inter-node interference, a start wavelength ID is assigned for each ingress node. A connection originating from one ingress node will adopt the corresponding start wavelength ID as the first one in its WSO and search the wavelengths by their IDs in an increasing and circular way to form its WSO. For example, start wavelength ID \(w\) leads to a WSO \([w, \ldots, w, 1, \ldots, w-1]\). The NFFTE scheme has two limitations. First, the interference concept cannot reflect the burst loss on each wavelength. Therefore, the NFFTE scheme based on this concept cannot efficiently adjust WSOs to reduce the overall burst loss contributed by the losses on different wavelengths. Second, the number of possible WSOs for one connection is limited by the number of wavelengths, which is very small compared with the number of possible WSOs, i.e., \(W!\). This is a serious limitation and may decrease the algorithm’s performance dramatically.

In this chapter, an offline wavelength assignment scheme is proposed. The

\(^1\)The explanation for these two schemes can be found in Section 2.1.2
key idea of the scheme is to generate the WSO of each connection according to the wavelength priorities, which are determined based on the estimated burst loss probabilities on the different wavelengths using a link model. Compared with the NFFTE scheme, our proposed scheme can make use of any possible WSOs instead of only a small set of WSOs, which can improve the ability of wavelength assignment in decreasing the burst loss probability. Meanwhile, a new link model is introduced to estimate burst loss on each wavelength. The efficiency of our proposed scheme is verified through simulation results.

This chapter is organized as follows. To begin with, the adopted link model is analyzed in Section 3.2. The proposed offline wavelength assignment scheme is presented in Section 3.3. Simulation results to evaluate the performance of the proposed wavelength assignment scheme are presented and discussed in section 3.4. Finally, concluding remarks are given in Section 3.5.

3.2 Link Model

In this section, we present our proposed link model. We also present an iteration method for determining the values of unknown variables in the model, which are required for calculating burst loss on a link.

3.2.1 Assumptions and Notations

Assume there are $L$ unidirectional links, $D$ connections and $W$ wavelengths per link in the network. Denote the WSOs of connections using a matrix $Q$ with dimensions $D \times W$, whose $d$th $(1 \leq d \leq D)$ row vector $\bar{q}_d$ is the WSO of the $d$th connection. WSO $\bar{q}_d$ is a permutation of the integers ranging from one to $W$. Totally, there are $W!$ possible permutations which constitute a permutation set $\hat{P}(W)$. For example, if $W$ is 2, $\hat{P}(W)$ should be $\{(1 \ 2), (2 \ 1)\}$.

As a general case, we assume the node preceding the unidirectional link $l$
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Figure 3.1: Target link

shown in Fig. 3.1 acts as an ingress node and also a core node. This node can be referred to as an integrated node and has appeared in earlier papers [73] [74]. Therefore, link $l$ has two kinds of input traffic, viz., locally generated traffic (local traffic) originating from the integrated node and transit traffic to be forwarded via link $l$ to downstream nodes. Its transit traffic is carried by $N$ input links. To facilitate discussion, we call the traffic within one input link as a transit stream and the local traffic as a local stream. Therefore, link $l$ has $N + 1$ input streams, which are labelled from zero to $N$: stream $n$ refers to the local stream when $n = 0$ and a transit stream when $1 \leq n \leq N$. Within stream $n$ $(0 \leq n \leq N)$, there are $M_n$ connections. Amongst these connections, the ones within a transit stream are named transit connections and those within the local stream are called local connections for link $l$.

Transit traffic has different stochastic characteristics from local traffic. Local traffic is generally assumed to be Poisson. However, transit bursts carried by one wavelength on one input link arrive sequentially, that is, the inter-arrival time between a burst and the immediate burst after it is always greater than its length. The input traffic of link $l$ can be described using the following notations.

- $\lambda_{w,n,m}$: traffic rate on wavelength $w$ of the $m$th $(1 \leq m \leq M_n)$ transit connection within transit stream $n$ $(1 \leq n \leq N)$
- $\lambda_{w,n}$: traffic rate on wavelength $w$ of the $n$th $(1 \leq n \leq N)$ transit stream, i.e., $\sum_{m=1}^{M_n} \lambda_{w,n,m}$
• $\lambda_{0,m}$: traffic rate of the $m$th ($1 \leq m \leq M_0$) local connection

• $\lambda_0$: traffic rate of the local stream, i.e., $\sum_{m=1}^{M_0} \lambda_{0,m}$

Furthermore, we assume burst length follows the exponential distribution with an average of $\frac{1}{\mu}$. Then the above-mentioned traffic rates can be mapped into corresponding traffic load by $\rho = \frac{\lambda_i}{\mu}$.

Given the traffic load information of link $l$, the offered loads of different wavelengths on link $l$ can be represented using an offered load matrix $S^l$ with dimensions $W \times (M_0 + N)$. The $w$th row vector $\bar{s}^l_w$ of $S^l$ is

$$
\bar{s}^l_w = [\rho_{w,0,1} \cdots \rho_{w,0,m} \cdots \rho_{w,0,M_0} \ \rho_{w,1} \cdots \rho_{w,n} \cdots \rho_{w,N}],
$$

(3.1)

where $\rho_{w,0,m}$ is the contribution of local connection $m$ to the offered load of wavelength $w$ and $\rho_{w,n}$ ($1 \leq n \leq N$) is $\frac{\lambda_{w,n}}{\mu}$. Similarly, the throughput $^2$ on wavelengths on link $l$ can be described using a throughput matrix $U^l$ with the same size as $S^l$. The $w$th row vector $\bar{u}^l_w$ of $U^l$ is

$$
\bar{u}^l_w = [\beta_{w,0,1} \cdots \beta_{w,0,m} \cdots \beta_{w,0,M_0} \ \beta_{w,1} \cdots \beta_{w,n} \cdots \beta_{w,N}],
$$

(3.2)

where $\beta_{w,0,m}$ is the throughput of local connection $m$ on wavelength $w$ on link $l$ and $\beta_{w,n}$ ($1 \leq n \leq N$) is the throughput of transit stream $n$.

The elements in $S^l$ and $U^l$ can be categorized into local and transit elements which are related to local and transit traffic, respectively. The values of the transit elements in $S^l$ are known from the traffic load information of link $l$. However, the values of the local elements in $S^l$ must be determined based on both local connections’ traffic load information (i.e., $\lambda_{0,m}$ for $1 \leq m \leq M_0$) and their WSOs, which will be explained in the next section. So, the unknown variables in $S^l$ and $U^l$ include the local elements in $S^l$ and all the elements in $U^l$. These variables’ relationships are reflected in the later proposed link model and their values can

---

$^2$Throughput in this thesis means utilization measured as the throughput (bps) normalized by wavelength capacity (bps).
be determined using an iteration method. Based on their values, the throughput on different wavelengths is known from $U_l$ and can be used 1) to determine the input traffic of downstream links, and 2) to determine the burst loss on link $l$ using the following formula, from which the network-wide burst loss performance can be determined directly.

$$\rho^l_{loss} = \rho_0 + \sum_{w=1}^{W} \sum_{n=1}^{N} \rho_{w,n}$$

$$- \sum_{w=1}^{W} M_0 \sum_{m=1}^{W} \beta_{w,0,m} - \sum_{w=1}^{W} \sum_{n=1}^{N} \beta_{w,n}$$

(3.3)

### 3.2.2 Link Model Description

Given the traffic load information of link $l$ and local connections’ WSOs, the objective of our proposed link model is to determine the relationships amongst unknown variables in $S_l$ and $U_l$. Considering that a burst belonging to local traffic can choose any available wavelengths while a burst belonging to transit traffic can only be assigned to its original wavelength, we introduce two sub-models in our proposed link model. The first sub-model is a one-wavelength contention model describing the contention situation on one wavelength. The second one is a multi-wavelength contention model illustrating the contention process of local traffic in the whole wavelength domain.

#### 3.2.2.1 One-Wavelength Contention Model

Consider wavelength $w$, which acts as an output channel on link $l$ and an input channel on an input link in Fig. 3.1. Similar to link $l$, the output channel has $N+1$ input streams defined in terms of wavelength $w$ instead of link $l$. Particularly, stream $n$ refers to the local stream when $n = 0$ and a transit stream when $1 \leq n \leq N$. The traffic load and rate of the $n$th ($1 \leq n \leq N$) transit stream are $\rho_{w,n}$ and $\lambda_{w,n}$, respectively. The idle length between two consecutive bursts within the transit stream $n$ is assumed to follow the exponential distribution with an average
value, denoted as $F_{w,n}$, determined using:

$$F_{w,n} = \frac{1}{\lambda_{w,n}} - \frac{1}{\mu}, \quad 1 \leq n \leq N. \quad (3.4)$$

The traffic load and rate of the local stream are $\rho_{w,0}$ and $\lambda_{w,0}$, respectively. By Eq. (3.1), we get

$$\rho_{w,0} = \frac{\lambda_{w,0}}{\mu} = \sum_{m=1}^{M_0} \rho_{w,0,m}. \quad (3.5)$$

In addition, as local connections have Poisson-distributed traffic rates, we assume the traffic of the local stream, which is contributed by these connections, is Poisson.

A $(N+1)$-dimensional Markov model can be developed based on the assumptions made above to describe the contention situation on one wavelength. Let $x_n$ ($1 \leq n \leq N$) represent the state of the $n$th input channel: $x_n = 1$ when it is busy and $x_n = 0$ otherwise. Let $y$ represent the state on the output channel: state $I$ denotes that the output channel is free and state $n$ ($0 \leq n \leq N$) means that the output channel is transmitting a burst belonging to stream $n$. Then a state in the model can be denoted as $(x_1, ..., x_N, y)$. The transition rates in the model are functions of $\lambda_{w,0}$ and $F_{w,n}$ ($1 \leq n \leq N$). In this model, however, there is no local balance equation, which means an equation array has to be resolved to determine its steady state probabilities. The following example illustrates this point. Assume $N$ is 4. Thus, state $(1,1,0,0,1)$ can convert to and from states $(1,1,1,0,1)$, $(1,1,0,1,1)$, $(1,0,0,0,1)$ and $(0,1,0,0,0)$, each of which can also convert to and from other multiple states.

From the computational complexity point of view, we want to avoid solving an equation array to determine the steady state probabilities of the one-wavelength contention model in wavelength assignment.\footnote{An offline wavelength assignment scheme will not introduce extra delay at the ingress nodes. Any update in the WSOs by it is done on a long term basis. However, it is still desirable to adopt reasonable assumptions and methods to make a scheme more computationally practical while sustaining its efficiency.} This is because these probabilities
have to be calculated repeatedly in the later proposed iteration algorithm for determining the values of unknown variables in matrices $S^l$ and $U^l$. Therefore, we introduce an approximate model with close-form steady state probabilities. The approximate model is a one-dimensional Markov model shown in Fig. 3.2, which only considers the states on the output channel: state $I$ denotes that the output channel is free and state $n$ means that the output channel is occupied by a burst from stream $n$ ($0 \leq n \leq N$). The transition rate $\nu_{w,n}$ from state $I$ to state $n$ is

$$
\nu_{w,n} = \begin{cases} 
\lambda_{w,0}, & n = 0; \\
\frac{1}{F_{w,n}} = \frac{\lambda_{w,n}}{1 - \rho_{w,n}}, & n > 0.
\end{cases} 
$$

(3.6)

The steady state probabilities in the model can be determined as follows. Let

$$
\vartheta_{w,n} = \frac{\nu_{w,n}}{\mu}.
$$

(3.7)

Let $\pi_n$ be the steady probability of state $n$ and $\pi_I$ of state $I$. We have

$$
\pi_n = \vartheta_{w,n} \pi_I, 
$$

(3.8)

$$
\pi_I + \sum_{n=0}^{N} \pi_n = 1.
$$

(3.9)

Hence,

$$
\pi_I = \frac{1}{1 + \sum_{n=0}^{N} \vartheta_{w,n}},
$$

(3.10)

$$
\pi_n = \frac{\vartheta_{w,n}}{1 + \sum_{n=0}^{N} \vartheta_{w,n}}, \quad 0 \leq n \leq N.
$$

(3.11)
Chapter 3. Priority-Based Offline Wavelength Assignment

Since only one wavelength is considered in the model, $\pi_n$ is in fact the throughput of stream $n$ on the output channel. Therefore,

$$\beta_{w,n} = \pi_n, \quad 0 \leq n \leq N.$$  \hspace{1cm} \text{(3.12)}

Based on $\beta_{w,n}$, the throughput of a connection on wavelength $w$ can be determined using

$$\beta_{w,n,m} = \beta_{w,n} \frac{p_{w,n,m}}{\rho_{w,n}}, \quad 1 \leq m \leq M_n.$$  \hspace{1cm} \text{(3.13)}

This one-wavelength contention model is an approximate one since $\nu_{w,n}$ ($n > 0$) defined in Eq. (3.6) is not accurate when there are multiple input streams, among which at least one stream is a transit one. As an example, consider bursts 1 and 2 overlap with each other and belong to different streams. Particularly, burst 2 is within transit stream $n$ ($1 \leq n \leq N$) and its header arrives when burst 1 is being transmitted by the output channel. So, burst 2 must be dropped since it cannot be allocated to the output channel. As a result, in the duration of burst 2, it is impossible that the output channel is occupied by a burst from transit stream $n$ while input channel $n$ is transmitting the dropped burst 2. Therefore, $\nu_{w,n}$ is zero in the duration of burst 2, which is different from what is defined in Eq. (3.6).

The model is accurate in two cases, namely, when there is only local traffic and when there is only one transit stream from an input channel. In the first case, the model becomes $M/M/1/1$ queuing model. In the second case, the throughput

---

4 We assume in this thesis that the conservation law holds or approximately holds when multiple traffic classes exist. Conservation law is that the overall loss probability (and hence the throughput) averaged over all traffic classes stays the same regardless of the number of classes and the degree of isolations [66]. Under this assumption, the throughput of a stream on an output channel is only determined by the traffic loads of the input streams to the channel.

5 In the presence of multiple traffic classes, the throughput of a connection within a stream on an output channel is in fact not only determined by its traffic load but also its traffic class which indicates the burst loss probability it experiences.
on the output channel equals the load of the transit traffic according to Eq. (3.11), or the burst loss is zero. This complies with the fact that bursts arrive in order from an input channel and thus experience no contention. The model’s accuracy in the second case is important, which is explained in Section 3.3.4.

### 3.2.2.2 Multi-wavelength Contention Model

We model the contention process of the local traffic in the whole wavelength domain in this section. A burst belonging to one local connection has to search the wavelengths sequentially for available resources within a delay bound. As soon as a free wavelength $w$ is found, the burst will be delayed appropriately and sent onto it. Therefore, the burst cannot contribute to the offered loads of the wavelengths that come after wavelength $w$ in the connection’s WSO. This process can be described using the following model:

\[
\rho_{q_m,1,0,m} = \rho_{0,m}, \\
\rho_{q_m,i,0,m} = \rho_{q_{m,i-1},0,m} - \beta_{q_{m,i-1},0,m}, \\
i = 2, 3, .., W, m = 1, ..., M_0.
\]

The model shows that the contribution of a local connection $m$ to the offered load of the first wavelength $q_{m,1}$ in its WSO $\bar{q}_m$ is always $\rho_{0,m}$, because all the bursts of connection $m$ will try to be allocated onto wavelength $q_{m,1}$ first. Its contribution to the offered load of wavelength $q_{m,i}$ ($i \geq 2$) is only the load that cannot be allocated to the previous $i - 1$ wavelengths in its WSO.

---

6We assume the $M_0$ local connections are the first $M_0$ connections in the network.
Table 3.1: Iteration method for determining the unknown values in $S^l$

1. Initialize: Initialize $S^{l,old}$ and $S^l$ using $\rho_{qm,i,0,m} = \rho_{0,m}$ (1 ≤ $m$ ≤ $M_0$) and $\rho_{qm,i,0,m} = 0$ for 2 ≤ $i$ ≤ $W$.

2. Update: Update local elements in $S^l$ for local connections in turn. For local connection $m$, the updating method is to calculate 

$$\rho_{qm,i,0,m} = \rho_{qm,i-1,0,m} - \beta_{qm,i-1,0,m},$$

where $i$ increases from 2 to $W$.

3. Loop: If \(\max_{i,j}(|s_{l,i,j} - s_{l,old,i,j}|) \leq \varepsilon\), terminate; else, $S^{l,old} = S^l$ and go to Step 2.

3.2.3 Iteration Method

3.2.3.1 Description

The proposed model shows the relationships among unknown variables including the local elements in the offered load matrix $S^l$ and all the elements within the throughput matrix $U^l$. Among these unknown variables, once the local elements in matrix $S^l$ are determined, the values of the elements within matrix $U^l$ can be deduced using the one-wavelength contention model. On the other hand, for the local elements in $S^l$, by Eqs. (3.6), (3.11), (3.13) and (3.15), we get

$$\rho_{qm,i,0,m} = \rho_{qm,i-1,0,m} - \frac{\rho_{qm,i-1,0,m}}{1 + \sum_{m'=1}^{M_0} \rho_{qm,i-1,0,m'} + \sum_{n=1}^{N} \frac{\rho_{qm,i-1,m}}{1 - \rho_{qm,i-1,m}}}.$$  \hfill (3.16)

Therefore, the link model is in fact a non-linear equation array to be solved, with the local elements in matrix $S^l$ as variables. This equation array is solvable because the number of equations is equal to the number of variables and there is no redundant equation. Nevertheless, it cannot be solved directly due to its non-linear property. We therefore propose an iteration method shown in Table 3.1.

The main idea in the iteration method is to update the values of the local elements in $S^l$ one by one until a terminating condition is satisfied. In the ini-
tialization stage, $S^l$ is initialized based on Eq. (3.14). In the updating stage, we update elements for the local connections in turn. During the updating procedure for a connection $m$, elements $\rho_{qm,2,0,m}, \ldots, \rho_{qm,W,0,m}$ will be updated in order based on Eq. (3.16). After all the local elements have been updated, a terminating condition will be checked: if the absolute value of the maximum relative change of the elements in $S^l$ is less than a threshold $\varepsilon$, the algorithm stops; otherwise, it continues.

### 3.2.3.2 Discussions

The above iteration method assumes that the unknown variables in an offered load matrix are the local elements. However, in a complete network, all the elements in an offered load matrix need to be determined. There are two reasons for this. First, a connection’s traffic load carried by one wavelength channel varies along its route because of burst loss. Second, integrated nodes may exist in the network, which inject additional traffic onto a route. In both cases, the values of the transit elements in an offered load matrix are unknown and determined by the throughput matrices of the corresponding upstream links. However, a throughput matrix is deduced from an offered load matrix. As a result, offered load matrices are coupled together and all the elements within them must be decided simultaneously.

Nevertheless, the iteration method may take a long time to converge if it is carried out for all the offered load matrices simultaneously due to the potentially large number of variables. This difficulty will disappear in an OBS network without integrated nodes, under the simplifying assumption that the traffic load of a connection carried by one wavelength remains the same along its route. In this case, the offered load matrix of each link preceded by an ingress node is only related to the link’s local connections and therefore can be determined separately. After that, based on the throughput matrices on these links, the input matrices of those links preceded by the core nodes can be decided directly. This observation will be used in our proposed offline wavelength assignment scheme.
Chapter 3. Priority-Based Offline Wavelength Assignment

3.3 Offline Wavelength Assignment Scheme

The proposed offline wavelength assignment scheme aims to determine the WSOs of connections to minimize network-wide burst loss. The assumption made in the scheme is that the traffic load of a connection carried by one wavelength remains the same along its route after its source node (the impact of this assumption on the scheme’s performance is discussed in Section 3.4). Three main steps construct the complete framework of the scheme, each of which is an independent algorithm. The three algorithms are a topology approximation algorithm, a priority-based FFTE algorithm, and a WSO extending algorithm in the wavelength domain. Because the second algorithm is the core one, we call our proposed scheme the priority-based FFTE (PFFTE) scheme. In this section, the details of the three algorithms are presented and the possible link models for the PFFTE scheme are also illustrated and compared.

3.3.1 Topology Approximation Algorithm

The topology approximation algorithm aims to reduce the complexity of solving link models in a network as explained in Section 3.2.3.2. In the algorithm, each integrated node is separated into an edge node and a core node connected by one bidirectional link consisting of two unidirectional links in opposite directions. Therefore, the original topology is replaced by an approximate one. After the topology approximation, there are only the edge and the core nodes in the network. Because of the similarity between the approximate and the original topologies, a WSO set that can work in the approximate topology can be expected to still work in the original one.
Table 3.2: Priority-based FFTE algorithm

1. Initialize: Initialize $Q$ and calculate $\rho_{\text{loss}}^{\text{old}}$.

2. Update: Set $G$ edge nodes as probing nodes in turn. For a probing node $g$ ($1 \leq g \leq G$), steps 2.1 and 2.2 are carried out.

   2.1 Determine the set of probing connections $\Omega$, backup $\bar{q}_i$ ($i \in \Omega$) as $\bar{q}_i^{\text{old}}$, redetermine $\bar{q}_i$ ($i \in \Omega$) and calculate $\rho_{\text{loss}}$;

   2.2 If $\rho_{\text{loss}} > \rho_{\text{loss}}^{\text{old}}$, restore $Q$ using $\bar{q}_i^{\text{old}}, i \in \Omega$; else, $\rho_{\text{loss}}^{\text{old}} = \rho_{\text{loss}}$.

3. Loop: If $(\rho_{\text{loss}}^{\text{old}} - \rho_{\text{loss}})/\rho_{\text{loss}} \leq \varepsilon$, terminate the algorithm; else, go to Step 2.

3.3.2 Priority-Based FFTE Algorithm

The priority-based FFTE algorithm is developed for an OBS network that only contains edge and core nodes. Motivated by the online wavelength assignment algorithm PWA proposed in [26], it repeatedly updates the WSOs of connections based on the wavelength priorities determined by calculated burst loss probabilities on the different wavelengths (in the PWA algorithm, by the feedback information from the network).

In the initialization step, each WSO in the WSO set $Q$ is set with an initial value, say from 1 to $W$. According to $Q$, the network-wide burst loss $\rho_{\text{loss}}$ can be calculated based on a link model. After the initialization step, WSOs of connections will be updated using an updating procedure. Assume the number of edge nodes is $G$. In one updating procedure, all the $G$ edge nodes in the network are set as probing nodes one by one. For a particular probing node, connections originating from it are referred to as probing connections, whose WSOs are updated at one time. The WSO updating for the probing connections is realized by probing and comparing the contention situations on different wavelengths for each probing connection: the lower the calculated end-to-end burst loss probability on a wavelength, the higher the priority of the wavelength, and a new WSO of a probing
connection is then set as the decreasing order of wavelengths regarding their priori-
ties. In doing so, it is expected that more traffic will be transmitted as throughput 
at the edge nodes on wavelengths with better contention situations to experience 
lower burst loss probability. After the WSO updating for all the probing connec-
tions, the network-wide burst loss will be re-calculated. If the new WSO set can 
lead to a lower network-wide burst loss, it will be accepted. Otherwise, WSOs of 
current probing connections are restored to their values before the updating. The 
algorithm will stop when the relative change of the network-wide burst loss after 
an updating procedure/iteration is less than a threshold $\varepsilon$.

In the proposed algorithm, the key point is to compare the relative contention 
situations on wavelengths based on the calculated end-to-end burst loss probabil-
ties of a probing connection on different wavelengths. To make a fair comparison, 
the connection’s throughput on different wavelengths at the probing node, i.e., its 
traffic loads carried by different wavelengths, should be of the same value. This 
value can be determined by assuming probing connections adopt random wave-
length assignment scheme simultaneously. Under this assumption, each burst from 
the probing node is allocated to a free wavelength randomly. Therefore, the total 
throughput of a probing connection evenly distributes on wavelengths. As an ex-
ample, consider probing connection $d$ which has a traffic load of $\rho_d$ and traverses 
link $l$ preceded by the probing node. Its throughput on a wavelength on link $l$, 
denoted as $\beta_d$, is

$$\beta_d = \beta_l \frac{\rho_d}{\rho_l} \frac{1}{W}, \quad (3.17)$$

where $\rho_l$ and $\beta_l$ are the local traffic load of link $l$ and total throughput on link $l$.
Since the local traffic is Poisson, $\beta_l$ can be determined using the Erlang B formula 
with $\rho_l$ as input.

The priority-based FFTE algorithm is a heuristic realized in an iterative man-
ner. It can terminate or converge after a limited number of iterations as proven 
below.
Claim 3.3.1. The priority-based FFTE algorithm terminates after a limited number of iterations.

Proof. Assume the calculated network-wide burst loss is $x^k$ after the $k$th iteration. According to the link model, it can be expected that $x^k$ has a positive lower bound $x^*$. In fact, as long as there is input traffic, the calculated burst loss at the edge nodes, which is a part of $x^*$, is always greater than zero due to the local traffic’s Poisson nature. In addition, according to the terminating condition, we have

$$0 < \varepsilon \leq \frac{x^k - x^{k+1}}{x^{k+1}},$$

which indicates $x^k > x^{k+1}$. Therefore, $x^k$ where $k \geq 1$ constructs a monotonically decreasing sequence with a lower bound. Hence, after a limited number of iterations, the priority-based FFTE algorithm terminates.

It is worth noting that the convergence point of the priority-based FFTE algorithm is not necessarily optimal. Nevertheless, later simulation results and related analysis show that the performance of the priority-based FFTE algorithm is good due to both its mechanism and the link model adopted by it.

3.3.3 WSO Extending Algorithm In The Wavelength Domain

The priority-based FFTE algorithm’s complexity is closely related to the number of wavelengths per link. Assume the average number of hops per connection is $H$. In one updating procedure, link models must be solved at each hop of the $D$ connections to update the WSOs of connections. Also, link models must be solved on all the $L$ links in the network to determine the network-wide burst loss after the WSOs of probing connections for each of the $G$ edge nodes are updated. Therefore, $DH + GL$ link models must be solved in one updating procedure. Meanwhile, the number of variables within a link model is proportional to the number of
Table 3.3: WSO extending algorithm

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Decide $\hat{W}$ which satisfies $\text{mod}(W, \hat{W}) = 0$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2</td>
<td>Decide $\hat{Q}$ in the compressed wavelength domain.</td>
</tr>
<tr>
<td>Step 3</td>
<td>Expand $\hat{Q}$ as $Q$ using $q_{d,p+j} = w_r + j, 0 \leq j \leq \frac{W}{\hat{W}} - 1$ where $w_r = (\hat{q}_{d,i} - 1) \cdot \frac{W}{\hat{W}} + 1$ and $p = (i - 1) \cdot \frac{W}{\hat{W}} + 1$ for $1 \leq d \leq D$ and $1 \leq i \leq \hat{W}$.</td>
</tr>
</tbody>
</table>

wavelengths. Therefore, when the number of wavelengths increases, the complexity of the priority-based FFTE algorithm increases.

The WSO extending algorithm aims to give an alternative choice to implement the priority-based FFTE algorithm with a lower complexity when the number of wavelengths $W$ is large. Let $\hat{W}$ be a factor of $W$. A wavelength domain with $\hat{W}$ wavelengths is referred to as a compressed domain relative to the original one. The priority-based FFTE algorithm only needs to be implemented in the compressed wavelength domain to decide a WSO set $\hat{Q}$. After that, required WSO set $Q$ can be obtained by mapping $\hat{Q}$ into the original wavelength domain. Each wavelength ID $\hat{w}$ in the compressed domain is mapped as a group of ordered wavelength IDs in the original wavelength domain. The start wavelength ID of the group is equal to $(\hat{w} - 1) \frac{W}{\hat{W}} + 1$ and the group members are wavelengths from $(\hat{w} - 1) \frac{W}{\hat{W}} + 1$ to $\hat{w} \frac{W}{\hat{W}}$. For example, if $W$ is 9, $\hat{W}$ can take 3. A WSO of $[1 3 2]$ in the compressed domain will be mapped as $[1 2 3 7 8 9 4 5 6]$ in the original domain. The detailed algorithm is presented in Table 3.3, with $\hat{Q}$ as input and $Q$ as output.

### 3.3.4 Possible Link Models In The PFFTE Scheme

The link model proposed in this chapter is not the only candidate model for the PFFTE scheme. The one-wavelength contention sub-model can be replaced by other existing models such as $M/M/1/1$, Engset [75], and the one proposed in [76].
to form new link models. These models differ from our proposed model in that they either consider only the total traffic load of an output channel or assume the input streams of an output channel have the same traffic load. We choose our proposed model as the basis of the PFFTE scheme since it can reflect the streamline effect, i.e., the impact of the relative load difference of the input streams on the burst loss performance on an output channel.

As an example, consider an output channel whose total input load is one Erlang from $N$ transit input streams. In one extreme case, all the traffic load concentrates to one input stream. Since bursts arrive orderly within the stream, there is no contention for the output channel among the bursts and thus the burst loss probability is zero. In another extreme case, these $N$ streams have the same load, i.e., $\frac{1}{N}$ Erlang, and $N$ is very large, which indicates that the input traffic can be approximately considered as Poisson. Therefore, burst loss probability is 50% by the M/M/1/1 queueing model. This example implies that it is desirable that the majority of the input traffic of an output channel comes from one input channel to form a dominant stream.

Since our model can reflect the contention process of bursts from different streams for an output wavelength, as can be seen from Fig. 3.2, the streamline effect is considered. An example is that when there is only one transit stream, burst loss is zero, as noted in Section 3.2.2.1.

### 3.4 Simulation Results

In this section, we use simulation experiments to evaluate the performance of the PFFTE scheme based on our proposed link model. The PFFTE scheme is mainly compared with the NFFTE scheme proposed in [24], since the NFFTE scheme is considered as the most efficient and stable algorithm to date. The main parameters and assumptions in the simulations are listed as follows:

- the transmission capacity of each wavelength channel is 10Gb/s;
the locally generated traffic at the edge nodes is Poisson;

- data burst length follows the exponential distribution with an average of 12.5kB, i.e., 10µs;

- the terminating threshold in the PFFTE scheme is $10^{-3}$;

- the terminating threshold in the iteration method to solve the link model is $10^{-6}$. 
Note that a stricter terminating threshold has been set to solve the link model, which is the calculation basis of the PFFTE scheme.

We consider two networks in the simulation experiments, viz., the 14-node NSFNET and a 16-node torus network, which represent irregular and regular network topologies, respectively. In addition, two structures of each topology are considered:

- integrated structure: there are only integrated nodes;

- edge/core structure: there are only edge and core nodes.

Take NSFNET as an example. There are 14 integrated nodes with the integrated structure (integrated NSFNET) while there are 14 core nodes and 14 edge nodes with the edge/core structure (edge/core NSFNET). Obviously, an edge/core network is the approximate topology of a corresponding integrated one. Therefore, WSO sets obtained in the edge/core networks can be directly adopted in the corresponding integrated networks.

In the simulation experiments, we assume there exists one connection between each source-destination node pair, whose route is decided using the shortest path routing algorithm. The traffic loads of connections are the same under identical traffic demand and follow an uniform distribution under non-identical traffic demand. The traffic load of the network, denoted as $\rho$ in this section, refers to the load of the bottleneck link under the shortest path routing scheme, i.e., link $8 \rightarrow 9$ in NSFNET and link $1 \rightarrow 2$ in the torus network. The value of $\rho$ is measured in Erlangs per wavelength. In the simulation experiments, we notice that the PFFTE algorithm can converge between 2-14 rounds. Also, we observe that the PFFET algorithm is insensitive to the order in which the probing nodes are considered.
Burst loss probabilities under the PFFTE scheme are compared with the ones under the NFFTE scheme in Figs. 3.5 - 3.8. Particularly, Figs. 3.5 and 3.7 are of NSFNET under identical and non-identical traffic demands, respectively, and Figs. 3.6 and 3.8 are of the torus network under identical and non-identical traffic demands, respectively. The number of wavelengths per link, i.e., $W$, in NSFNET is 14 and in the torus network is 16, which is especially set to implement the NFFTE scheme (in the sequel, unless otherwise stated, $W$ takes the same value as in this part). It can be seen from the simulation results that the PFFTE scheme outperforms the NFFTE scheme in both the integrated and the edge/core networks. Quantitatively, the performance advantage of the PFFTE scheme over the NFFTE scheme, i.e., $(p_{\text{loss}}^{\text{NFFTE}} - p_{\text{loss}}^{\text{PFFTE}})/p_{\text{loss}}^{\text{NFFTE}}$, is plotted against the traffic load in Fig. 3.9 and Fig. 3.10 under identical and non-identical traffic demands, respectively. It is suggested that the lighter the traffic load, the larger the performance advantage of the PFFTE scheme over the NFFTE scheme. This phenomenon can be expected due to the simplifying assumption made in the PFFTE scheme: the traffic load of a connection carried by one wavelength remains the same along its route. Such an assumption is adopted to make it easier to decide the offered load matrices at the core nodes. Under this assumption, a lighter traffic load implies more accurate estimations of offered load matrices and related calculations in the PFFTE scheme, leading to a better performance of the PFFTE scheme.

To explain why the PFFTE scheme performs better than the NFFTE scheme, the PFFTE scheme using the M/M/1/1 queuing model as the one-wavelength contention sub-model, i.e., the PFFTE-MM11 scheme, is also implemented in the simulation experiments. Simulation results in Figs. 3.5 - 3.8 show that the PFFTE-MM11 scheme performs in between the PFFTE scheme and the NFFTE scheme. This shows that there are two reasons of the good performance of the PFFTE scheme. The first reason, as explained before, is that the PFFTE scheme overcomes the mechanism shortcomings of the NFFTE scheme. Specifically, a
WSO in the PFFTE scheme can be any permutation of integers ranging from 1 to $W$, while there are only $W$ candidate WSOs in the NFFTE scheme. The second reason is the better accuracy of the link model adopted in the PFFTE scheme, which is proven by the fact that the PFFTE scheme has a better performance compared with the PFFTE_MM11 scheme.

### 3.4.2 Effect Of Delay Bound At Edge Nodes And Number Of Wavelengths Per Link

Intuitively, the effect of FFTE schemes is to isolate the connections’ traffic loads to different wavelengths. Therefore, the larger the number of wavelengths, the better the isolation effect. In addition, the delay bound at the edge nodes can also affect the isolation degree. A longer delay bound means that the traffic of one connection will concentrate to a few wavelengths and be separated from the other.
connections more fully. So, it is expected that the performance of FFTE schemes can be enhanced by prolonging the delay bound at the edge nodes.

Burst loss probabilities under the PFFTE scheme and the NFFTE scheme are presented against the delay bound at the edge nodes in Figs. 3.11 and 3.12 when the traffic load is 0.5 or 0.8 under non-identical traffic demand, with Fig. 3.11 for integrated networks and Fig. 3.12 for edge/core networks. Similarly, the results when the number of wavelengths per link increases from $W$ to $4W$ are plotted in Fig. 3.14 and 3.14 under non-identical traffic demand, with Fig. 3.13 for integrated networks and Fig. 3.14 for edge/core networks. In these cases, when the number of wavelengths per link is greater than $W$, WSO matrix $Q$ is deduced from $\hat{Q}$ obtained in the wavelength domain with $W$ wavelengths using the WSO extending algorithm. In these simulation scenarios, the edge/core structure is assumed. Simulation results show that the WSO extending algorithm can reduce the complexity of the PFFTE scheme efficiently while retaining its performance.

Figure 3.6: Performance of FFTE schemes in the torus network vs. the traffic load under identical traffic demand (16 wavelengths per link and zero delay bound at the edge nodes)
advantage over the NFFTE scheme. More importantly, simulation results also indicate that burst loss probability decreases under both the PFFTE scheme and the NFFTE scheme to some degree when the delay bound and the number of wavelengths increase. However, the performance advantage of the PFFTE scheme over the NFFTE scheme given in Table 3.4 indicates that the PFFTE scheme can benefit more compared with the NFFTE scheme.

To explain the above phenomenon, we first show that the overall input load of an output channel preceded by a core node\(^7\), say wavelength \(w\) on an output link \(l\) after a core node \(g\), tends to be unchanged with the increasing number of wavelengths and delay bound under a fixed traffic load measured in Erlangs per wavelength. First, according to the multi-wavelength contention model, the contribution of a connection to the offered load of a wavelength depends on the

\footnote{The explanation presented here can be modified in a straightforward manner to be used in the case of integrated nodes’ output channels.}
Figure 3.8: Performance of FFTE schemes in the torus network vs. the traffic load under non-identical traffic demand (16 wavelengths per link and zero delay bound at the edge nodes)

position of the wavelength within the connection’s WSO. Specifically, the farther the wavelength to the first position of a connection’s WSO, the less the contribution of the connection to the offered load of the wavelength. Since wavelength $w$ is likely to be uniformly located within the WSOs of connections traversing link $l$ under either the PFFTE scheme or the NFFTE scheme, its offered load contributed by these connections is equal to that when wavelength $w$ is in the middle of these connections’ WSOs, which is the sum of average throughput per wavelength of these connections on the input links of node $g$. Second, since the burst loss probability of each connection at its ingress node is usually small, the average throughput per wavelength of a connection on a particular link does not change much with the increasing number of wavelengths and delay bound.

With the input load of an output channel not changing much, the relative load difference among its input streams determines the burst loss on it, according to the discussion in Section IV-D. The NFFTE scheme, however, does not consider the
traffic loads of individual streams of an output channel, leading to its inefficiency in controlling the relative traffic loads of input streams. Hence, the performance of the NFFTE scheme is mainly determined by the overall input load of each output channel and therefore alters slightly. On the contrary, the PFFTE scheme is based on stream load analysis. So, it is potentially capable of benefiting more from the increases in the number of wavelengths and delay bound, which provide more flexibility in controlling the relative input stream loads.

3.5 Summary

In this chapter, we have studied the wavelength assignment problem in non-wavelength-convertible OBS networks. An offline wavelength assignment scheme, i.e., the PFFTE scheme, has been proposed. The convergence of this scheme has been proven theoretically. We have conducted computer simulations in regular
Figure 3.10: Performance advantage of the PFFTE scheme over the NFFTE scheme vs. the traffic load under non-identical traffic demand ($W$ wavelengths per link and zero delay bound at the edge nodes) and irregular networks. Compared with other schemes, the PFFTE scheme can significantly reduce the burst loss probability. We also have used simulation experiments to analyze the reasons of this performance improvement. Simulation results indicate that it is due to both the mechanism and the link model adopted by the PFFTE scheme. Furthermore, simulation results illustrate that the performance of PFFTE scheme can be enhanced by a larger number of wavelengths per link and a reasonable delay bound at the edge nodes.
Figure 3.11: Effect of the delay bound at the edge nodes in integrated networks under non-identical traffic demand ($W$ wavelengths per link)

Figure 3.12: Effect of the delay bound at the edge nodes in edge/core networks under non-identical traffic demand ($W$ wavelengths per link)
Figure 3.13: Effect of the number of wavelengths per link in integrated networks under non-identical traffic demand (zero delay bound at the edge nodes)

Figure 3.14: Effect of the number of wavelengths per link in edge/core networks under non-identical traffic demand (zero delay bound at the edge nodes)
Table 3.4: Performance advantage of the PFFTE scheme over the NFFTE scheme with the change of delay bound at the edge nodes and the number of wavelengths per link under non-identical traffic demand

<table>
<thead>
<tr>
<th>number of wavelengths</th>
<th>delay bound</th>
<th>$\rho = 0.5$</th>
<th>$\rho = 0.8$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0$\mu$s</td>
<td>25$\mu$s</td>
<td>50$\mu$s</td>
</tr>
<tr>
<td>edge/core NSFNET</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho = 0.5$</td>
<td>58%</td>
<td>86%</td>
<td>92%</td>
</tr>
<tr>
<td>$\rho = 0.8$</td>
<td>25%</td>
<td>58%</td>
<td>70%</td>
</tr>
<tr>
<td>edge/core torus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho = 0.5$</td>
<td>67%</td>
<td>86%</td>
<td>92%</td>
</tr>
<tr>
<td>$\rho = 0.8$</td>
<td>46%</td>
<td>71%</td>
<td>79%</td>
</tr>
<tr>
<td>integrated NSFNET</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho = 0.5$</td>
<td>57%</td>
<td>80%</td>
<td>86%</td>
</tr>
<tr>
<td>$\rho = 0.8$</td>
<td>30%</td>
<td>58%</td>
<td>68%</td>
</tr>
<tr>
<td>integrated torus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho = 0.5$</td>
<td>64%</td>
<td>83%</td>
<td>89%</td>
</tr>
<tr>
<td>$\rho = 0.8$</td>
<td>46%</td>
<td>66%</td>
<td>74%</td>
</tr>
</tbody>
</table>
Chapter 4

Wavelength Converter Allocation

4.1 Introduction

Since WCs (especially FWCs) are expensive and still immature technically, it is desirable to reduce the number of WCs in a network and to have partial wavelength conversion capability at the core nodes when WCs are used to resolve contentions among bursts for output wavelengths. This is usually realized using share-per-node (SPN) and share-per-link (SPL) WC deployment structures [2].

The allocation of WCs at the core nodes in a partially wavelength-convertible network can affect the burst loss probability since different nodes experience different degrees of burst contentions. In this paper, the converter allocation problem that we focus on is: Given T WCs and traffic loads of connections between node pairs, how to distribute the converters over the core nodes in an OBS network so as to minimize the burst loss probability?

The converter allocation problem we focus on has been extensively studied in the literature on optical circuit switching (OCS), where the QoS metric is the call blocking probability [29][30][31][32]. In [29], the authors investigate the performance of the uniform converter allocation scheme, i.e., each node being equipped with the same number of converters. In [30], a simulation-based optimization ap-
proach is proposed. This technique aims to reduce the blocking probability by optimizing a converter utilization metric, which is derived from the converter utilization statistics gathered from computer simulations. Another simulation-based algorithm is proposed in [31]. In [32], an analysis-based approach is presented. In this technique, converters are deployed in turn. For each converter, a core node is chosen so that the best call blocking performance is generated. The performance is estimated using an analytical model. These algorithms proposed for OCS can be applied in OBS after some modifications are made if necessary (e.g., in the analysis-based approach, the model should be substituted by a model for estimating the burst loss probability). However, these algorithms’ efficiency in OBS should be re-evaluated since OCS and OBS differs in a significant way that affects their QoS performance. In OBS, the relative load difference between the traffic streams from different input links significantly affects the burst loss performance at an output link, as highlighted in [80] where we introduced the term streamline effect. This is caused by the fact that bursts arrive in an orderly manner within a stream. In OCS, however, the call arrivals are always assumed to be Poisson [29][30][31][32]. As a result, the converter allocation algorithms proposed for OCS can only be regarded as a reference and the converter allocation problem needs to be re-studied in OBS. To be best of knowledge, there is no related work in the literature.

In this chapter, we propose a greedy analysis-based algorithm, which is similar to the one presented in [32]. We prove the algorithm is optimal in minimizing the burst loss probability, assuming as in [24] and [39] that the reduction in the traffic loads on connections at downstream links can be ignored (referred to as the constant-load assumption). In addition, we introduce a link model for estimating the burst loss probability. Compared with the existing models in the literature [77][23][76], this model can reflect the streamline effect, which is detailed in Section 4.3.

This chapter is organized as follows. The proposed WC allocation algorithm is presented in Section 4.2. Section 4.3 illustrates the link model. Simulation results are shown and analyzed in Section 4.4. Finally, we conclude in Section 4.5.


4.2 Wavelength Converter Allocation Problem

In this section, we introduce an integer programming formulation of the WC allocation problem in OBS networks and propose a greedy algorithm which we show to be optimal under the constant-load assumption.

4.2.1 WC Allocation Problem Formulation

We consider the WC allocation problem in an OBS network with the SPL WC deployment structure and without FDLs. We assume that the core nodes do not function as the edge nodes, i.e., we consider the edge/core network defined in Chapter 3. In this case, only transit traffic appears at the core nodes.

Within the network, there are \( L \) output links from the core nodes, each with \( W \) wavelengths. An output link \( l \) has \( N \) input traffic streams (the value of \( N \) may be different for link \( l_1 \) and link \( l_2 \) if \( l_1 \neq l_2 \)), each from an input link and the \( n \)th \((1 \leq n \leq N)\) stream has a traffic load of \( \rho_{l,n} \). The values of \( \rho_{l,n} \) for \( 1 \leq n \leq N \) form a vector \( \overline{\rho}_l \) that describes the input traffic load for link \( l \). Assume there are \( C \) \((1 \leq C \leq W)\) WCs within the WC bank of link \( l \). The formula for estimating burst loss on link \( l \) can be denoted as \( f(\overline{\rho}_l, C) \), which will be explained in Section 4.3 based on a link model.

The integer programming formulation for the optimal allocation of \( T \) WCs in an OBS network is thus:

\[
\text{Minimize} \quad \sum_{l=1}^{L} f(\overline{\rho}_l, \sum_{w=1}^{W} x_{l,w}) \\
\text{Subject to} \quad \sum_{l=1}^{L} \sum_{w=1}^{W} x_{l,w} = T; \\
\quad x_{l,w} \geq x_{l,w+1}; \\
\quad x_{l,w} \in \{0, 1\},
\]

where \( 1 \leq l \leq L, 1 \leq w \leq W \) and \( x_{l,w} \) is the binary variable (as shown in the
third constraint) to be optimized. When $x_{l,w} = 1$, at least $w$ WCs are allocated to link $l$; when $x_{l,w} = 0$, less than $w$ WCs are allocated (as guaranteed in the second constraint). As a result, the number of WCs allocated within the WC bank of link $l$ is $w$, or $\sum_{w=1}^{W} x_{l,w}$, if $x_{l,1} = \ldots = x_{l,w} = 1$ and $x_{l,w+1} = \ldots = x_{l,W} = 0$. The objective of the optimization is to minimize the sum of burst loss on the different links, which amounts to minimizing the burst loss probability in the network given the total traffic load. The overall number of WCs to be allocated forms the first constraint.

Note that although the WC allocation formulation is introduced under the assumption of the SPL WC deployment architecture and the absence of FDLs, it can be directly applied in the presence of FDLs and modified in a straightforward manner to be used in the cases of other WC deployment architectures. Similarly, the WC allocation algorithm proposed in the next section and the proof for its optimality can be applied under such different assumptions.

### 4.2.2 WC Allocation Algorithm

The optimal solution to the above integer programming formulation is difficult to determine using traditional methods for integer linear programming (ILP) problems. The reason is that its objective function neither has a close form (which is shown in Section 4.3) nor can be easily piecewise linearized due to the presence of multiple input arguments. Our proposed algorithm is shown in Table 4.1.

In this algorithm, the number of WCs within the WC bank of each link is assumed as $W$ initially. So, the total number of WCs is $LW$ in the beginning. Then, $LW - T$ WCs are removed one by one. Specifically, a WC is removed from a WC bank such that the smallest increase in burst loss is caused. The algorithm terminates when the number of WCs in the network is $T$.

To determine the WC bank for a WC to be removed in a simple way, we
assume the traffic load of a connection remains the same along its route. That is,

$$\rho_{l,n} \approx \sum_{(l,n) \in r^d} \rho^d, 1 \leq d \leq D, \quad (4.2)$$

where $D$ is the total number of traffic connections in the network, $r^d$ is the route of connection $d$, $\rho^d$ is the traffic load on connection $d$ at its ingress node and $(l, n)$ is the $n$th input link to link $l$. The constant-load assumption is reasonable for our proposed converter allocation algorithm since burst loss in the network can be maintained at a low level before the overall number of WCs is reduced to $T$ considering the fact that WC allocation generally aims to form a partially wavelength-convertible OBS network with acceptable burst loss.

Under the constant-load assumption, the input traffic load for each output link does not change with the allocation of WCs in the network. So, the increase in network-wide burst loss after a WC is removed from the WC bank of a link $l$ is equal to the increase in burst loss on link $l$, which is denoted as $g_l(\rho_l, C^q_l)$ and defined as

$$g_l(\rho_l, C^q_l) \equiv f(\rho_l, C^q_l - 1) - f(\rho_l, C^q_l),$$

$$1 \leq C^q_l \leq W, 1 \leq l \leq L, \quad (4.3)$$
where \( C^q_l \) is the number of WCs inside the WC bank of link \( l \) when the \( q \)th (\( 1 \leq q \leq LW \)) WC is to be removed from the network. Therefore, the \( q \)th WC should be removed from the WC bank of a link with the smallest \( g_l(\bar{\rho}_l, C^q_l) \).

The optimality of the proposed converter allocation algorithm is proved below.

**Theorem 4.2.1.** : Under the constant load assumption, the \( T \) FWCs in the network are optimally allocated after \( (LW-T) \) converters are removed using the proposed FWC allocation algorithm.

**Proof.** Let \( l^* \) be the link from the converter bank of which the \( q \)th WC is removed (link \( l^* \) may be different for the \( q_1 \)th WC and the \( q_2 \)th one if \( q_1 \neq q_2 \)). Under the constant-load assumption,

\[
\sum_{l=1}^{L} f(\bar{\rho}_l, C^{q+1}_l) - \sum_{l=1}^{L} f(\bar{\rho}_l, C^q_l) = g_{l^*}(\bar{\rho}_{l^*}, C^{q}_{l^*}), \tag{4.4}
\]

\( 1 \leq C^{q}_{l^*} \leq W, 1 \leq l^* \leq L, 1 \leq q \leq LW - T. \)

As a result, when there are \( T \) converters in the network or after \( (LW - T) \) WCs are removed, the increase in total burst loss in the network is

\[
\sum_{l=1}^{L} f(\bar{\rho}_l, C^{LW-T+1}_l) - \sum_{l=1}^{L} f(\bar{\rho}_l, C^1_l) = \sum_{q=1}^{LW-T} g_{l^*}(\bar{\rho}_{l^*}, C^{q}_{l^*}), \tag{4.5}
\]

where \( \sum_{l=1}^{L} f(\bar{\rho}_l, C^{LW-T+1}_l) = \sum_{l=1}^{L} f(\bar{\rho}_l, \sum_{w=1}^{W} x_{l,w}) \) and the values of \( x_{l,w} \) (\( 1 \leq l \leq L, 1 \leq w \leq W \)) can be determined based on the definition of \( x_{l,w} \) in Eq. (4.1). We know that \( \sum_{l=1}^{L} f(\bar{\rho}_l, C^1_l) \) is equal to \( \sum_{l=1}^{L} f(\bar{\rho}_l, W) \) which is a constant value, given the traffic load of the network. Meanwhile, \( \sum_{q=1}^{LW-T} g_{l^*}(\bar{\rho}_{l^*}, C^{q}_{l^*}) \) is minimized since it is the sum of the smallest \( (LW - T) \) values that, by the algorithm, \( g_{l^*}(\bar{\rho}_{l^*}, C^{q}_{l^*}) \) can take when \( 1 \leq q \leq LW - T \). Therefore, according to Eq. (4.5), the value of \( \sum_{l=1}^{L} f(\bar{\rho}_l, C^{LW-T+1}_l) \), i.e., the overall burst loss in the network, is minimized or the \( T \) WCs are optimally allocated after \( (LW - T) \) WCs are removed.
4.3 Link Model

In this section, we first examine the existing input traffic assumptions and present a new assumption. Under the new assumption, we develop a link model for estimating the burst loss on an output link. Compared with the one-wavelength link model introduced in Section 3.2.2.1, this model is a generalized one where different wavelength conversion capabilities are allowed.

4.3.1 Input Traffic Assumption

The number of input streams to link $l$ is $N$, with the $n$th one from node $n$ and having traffic load $\rho_{l,n}$. The number of wavelengths per link is $W$. The number of WCs within the WC bank for link $l$ at node $A$ is $C$. Thus, the conversion ratio is $\frac{C}{W}$ on link $l$. WCs are of circular type, i.e., a WC with conversion capability $D_c$ can convert an input wavelength $x$ ($1 \leq x \leq W$) to an output wavelength $y$ ($1 \leq y \leq W$) if $|x - y| \leq D_c$ or $|x \pm W - y| \leq D_c$. The conversion degree or the number of wavelengths that a WC can convert its input wavelength to, denoted as $D_d$, is $2D_c + 1$. If $D_d \geq W$, a WC is an FWC; otherwise, it is an LWC. The reservation for a burst on a wavelength is from its start time to its end time as defined in the Just-Enough-Time (JET) signaling protocol [7]. We assume the offset is zero. We also assume bursts are scheduled using CAS algorithm. By this algorithm, a burst arriving from a wavelength (i.e., its incoming wavelength) is allocated to its incoming wavelength on its output link if the wavelength is free;
otherwise, the burst is allocated using the *latest available unused channel with void filling* (LAUC-VF) algorithm [7], by which a free wavelength, if any, on the burst’s output link is chosen for the burst. A WC is used when a burst is allocated to a wavelength on its output link which is different from its incoming wavelength.

A link model can be introduced under the Poisson assumption for burst arrivals [23][77]. However, as indicated in Chapter 3, the streamline effect [37] is not considered in this case and it does not comply with the fact that bursts come from a limited number of input wavelengths. An alternative burst arrival assumption is that the lengths of ON/OFF periods formed by bursts on an input wavelength follow exponential distributions. Under this assumption, the burst loss performance at an output link can be determined using a Markov chain model, where a state is a vector composed of the individual states, either busy or free, of the input and the output wavelengths. Since the number of its dimensions increases with the number of wavelengths and the number of input streams, this model is highly computationally unscalable. Under the same burst arrival assumption, there are two-dimensional Engset model and a three-dimensional model developed in [76]. However, both of them exclude the streamline effect. Besides, the Engset model assumes that on an input wavelength bursts continue arriving in the duration of a burst which is also from this wavelength and has been dropped. This is not true in the real situation [76].

We assume the traffic from an input stream to be truncated Poisson, which is formed after Poisson traffic is sent onto a link with full wavelength conversion capability. In other words, the distribution of the number of bursts arriving from the nth input stream at a time, denoted as $M_n$, can be determined using the M/M/W/W queuing model as follows:

$$P(M_n = i) = \frac{(\rho_{l,n})^i / i!}{\sum_{w=0}^{W} (\rho_{l,n})^w / w!},$$

$$0 \leq i \leq W, 1 \leq n \leq N.$$  \hspace{1cm} (4.6)

One reason for this assumption is that the input traffic at an edge node is usu-
ally assumed to be Poisson [77][39]. Besides, as we explain later, this assumption helps us to develop a Markov chain model which not only can reflect the stream-line effect but also is two-dimensional which implies relatively lower computational complexity.

Under the truncated Poisson traffic assumption, an input stream of node A can be considered to be formed after Poisson traffic, i.e., a Poisson stream, passes though a fully wavelength-convertible core node. Therefore, nodes 1 to $N$ in Fig. 4.1(a) can be assumed to be fully wavelength-convertible. The traffic load for the $n$th Poisson stream, denoted as $\rho_{l,n}^*$, is not equal to $\rho_{l,n}$, but should be calculated using

$$\rho_{l,n} = \rho_{l,n}^* \left(1 - \frac{(\rho_{l,n}^*)^W/W!}{\sum_{w=0}^{W}(\rho_{l,n}^*)^w/w!}\right).$$

(4.7)

### 4.3.2 Burst Loss Estimation

We need to simplify the system architecture shown in Fig. 4.1(a) to the system shown in Fig. 4.1(b) so as to develop a desirable model. Before giving the reasons for the simplification and the details of the simplified system, we first briefly describe the simplified system.

In Fig. 4.1(b), the output link of node B is deployed with the same number of WCs and the same type of WCs as link $l$ in Fig. 4.1(a). The input of node B is Poisson traffic with a load equal to the sum of input traffic load for nodes 1 to $N$ in Fig. 4.1(a), i.e., $\sum_{n=1}^{N}\rho_{l,n}^*$. The Poisson traffic for node B still consists of $N$ Poisson streams and the load of a stream is determined using Eq. (4.7). The scheduling algorithm/policy at node B is virtual CAS (VCAS) which is only for theoretical analysis in this section and cannot be implemented physically or simulated. The aim of VCAS is to make the throughput on the output link of node B equal that on link $l$ in theory. Denoting the throughput as $\beta$, we can determine the value of $\beta$ based on the simplified architecture shown in Fig. 4.1(b) and then the burst loss
\( \rho_{\text{loss}} \) on link \( l \) using

\[
\rho_{\text{loss}} = \sum_{n=1}^{N} \rho_{l,n} - \beta. \tag{4.8}
\]

There are two reasons for the simplification. First, compared with the link \( l \) in Fig. 4.1(a), the input traffic to the output link in the simplified architecture follows the Poisson process, which is enabled by the truncated Poisson assumption as indicated in Eq. (4.7). With Poisson input traffic, we can develop a two-dimensional model. Second, as to be explain later, the streamline effect can be modelled using the simplified architecture.

As mentioned above, VCAS at node B should be designed to make the throughput on the output link of node B equal that on link \( l \). To do that, the VCAS scheme should be designed so that the burst loss at node B in Fig. 4.1(b) equals the total burst loss at nodes A and 1 to \( N \) in Fig. 4.1(a) when the \( N \) Poisson input streams are considered as the input traffic. In Fig. 4.1(a), burst loss occurs when the number of bursts arriving simultaneously is larger than the number of wavelengths per link. For this type of burst loss, there is no difference in Fig. 4.1(a) and Fig.4.1(b) whatever the burst scheduling policy is. Burst loss also occurs when there is no free WC to allocate bursts to free output wavelengths or free wavelengths are out of the conversion range of WCs. In Fig. 4.1(a), this kind of burst loss only occurs at node A. At nodes 1 to \( N \), contentions among bursts within a same Poisson stream for an output wavelength are resolved without being affected by the number or the conversion range of WCs since these nodes are fully wavelength-convertible. Meanwhile, it can be observed the WCs are used only in the case of intra-stream contention at nodes 1 to \( N \): A burst belonging to Poisson stream \( n \) arrives from wavelength \( x \) while wavelength \( x \) on the output link of node \( n \) is busy due to another burst which is also from Poisson stream \( n \). There is no inter-stream contention at nodes 1 to \( N \) since bursts from different Poisson streams have different output links. Therefore, to emulate the full wavelength conversion capability at nodes 1 to \( N \), we assume no WC needs to be used and a burst can be allocated to any
wavelength on the output link when intra-stream contentions occur at node $B$. This forms the difference between VCAS and CAS schemes. Assuming below is the probability that two bursts contending for an output wavelength at node $B$ are both from Poisson stream $n$:

$$
\left( \frac{\rho_{l,n}^*}{\sum_{n=1}^{N} \rho_{l,n}^*} \right)^2,
$$

(4.9)

we have following probability, denoted as $p$, that a contention between two bursts is intra-stream at node $B$:

$$
p = \sum_{n=1}^{N} \left( \frac{\rho_{l,n}^*}{\sum_{n=1}^{N} \rho_{l,n}^*} \right)^2.
$$

(4.10)

With the simplified system, the throughput on the output link of node $B$ in Fig. 4.1(b) can be determined from a two-dimensional Markov chain model. A state in the model is denoted as $(i, j)$, $0 \leq i \leq W$, $j \leq i$ and $j \leq C$, indicating that $i$ wavelengths are busy (i.e., reserved) on the output link with $j$ WC's in use. Let $\frac{1}{\mu}$ be the average burst length and $\lambda$ equal $\mu \sum_{n=1}^{N} \rho_{l,n}^*$. Assuming a burst arrives from any one of the $W$ wavelengths with equal probability$^1$, we have the following transition rates in the model, where $A_{i,j}^{a,b}$ is the transition rate from state $(i, j)$ to state $(i + a, j + b)$, with $A_{i,j}^{a,b}$ being zero when $0 \leq i + a \leq W$ or $0 \leq j + b \leq \min(C, i + a)$ is not met.

- $A_{i,j}^{0,0} = \lambda (\frac{W-i}{W} + \frac{1}{W} p)$: In this case, the incoming bursts are allocated without the use of WC's. This happens when their incoming wavelengths on the output link are free. Such burst arrival rate is $\lambda \frac{W-i}{W}$. This can also happen when their incoming wavelengths on the output link are busy due to bursts from the same Poisson streams. The burst arrival rate in this case is $\lambda \frac{1}{W} p$.

- $A_{i,j}^{1,1} = \lambda \frac{1}{W} (1 - p)(1 - \gamma_i)$: In this case, the incoming bursts are allocated using WC's ($\gamma_i$ is explained below).

$^1$Even when $T$ is very small, this assumption is reasonable since wavelengths on output links are chosen randomly for bursts with equal probability.
• $A_{i,j}^{-1,0} = (i - j)\mu$: In this case, bursts are transmitted onto the output link without the aid of WCs.

• $A_{i,j}^{-1,-1} = j\mu$: In this case, bursts are transmitted onto the output link with the aid of WCs.

In the above expressions of transition speeds,

$$
\gamma_i = \begin{cases} 
0, & i < D_d; \\
\frac{i}{W} - \frac{i-D_d+1}{W}, & i \geq D_d,
\end{cases}
$$

(4.11)

is the probability that all the wavelengths within the conversion range of WCs are busy.

Let $\pi_{i,j}$ be the steady state probability of state $(i, j)$. The value of $\pi_{i,j}$ can be determined by solving the following global balance equations:

$$
\pi_{i,j}(A_{i,j}^{1,0} + A_{i,j}^{1,1} + A_{i,j}^{-1,0} + A_{i,j}^{-1,-1}) = A_{i-1,j}^{1,0}\pi_{i-1,j} + A_{i-1,j-1}^{1,1}\pi_{i-1,j-1} + A_{i+1,j}^{-1,0}\pi_{i+1,j} + A_{i+1,j+1}^{-1,-1}\pi_{i+1,j+1},
$$

(4.12)

$0 \leq i \leq W, 0 \leq j \leq \min(C, i)$.

Then the throughput on the output link of node B is

$$
\beta = \sum_{i=1}^{W} \sum_{j=0}^{\min(C,i)} i\pi_{i,j},
$$

(4.13)

and the burst loss on link $l$ can be determined using Eq. (4.8). From Eqs. (4.7) (4.8) (4.10) (4.13), it can be seen that the burst loss performance on link $l$ changes with $C$ and $\rho_l,n$ or $\overline{\rho}_l$, which is why we denoted it as $f(\overline{\rho}_l, C)$ in the previous section.

This link model can reflect the streamline effect. Consider the case of two input streams. Assume the traffic loads of the two streams are $\rho_{l,1} = r\rho$ and $\rho_{l,2} = (1 - r)\rho$, respectively, where $\rho$ is the overall traffic load and $0 \leq r \leq 1$. The
value of $r$ indicates the relative load difference between the two streams. When $r = 0.5$, the two streams have the same load. When $r = 0$ or $r = 1$, all traffic arrives from one stream and the relative load difference between the two streams is the largest. We assume $\rho_{i,1}^* \approx \rho_{l,1}$ and $\rho_{i,1}^* \approx \rho_{l,1}$, where $\rho_{i,1}^*$ and $\rho_{i,2}^*$ are the Poisson input traffic loads for the two streams and should be determined using Eq. (4.7). The value of $p$ is therefore equal to $r^2 + (1 - r)^2$ or $2(r - 0.5)^2 + 0.5$ according to Eq. (4.10). It is evident that when $r = 0.5$, $p$ has its minimum value of 0.5. When $|r - 0.5|$ increases, $p$ becomes larger. Specifically, when $r = 1$ or $r = 0$, $p$ takes its largest value of 1. Meanwhile, the value of $A_{i,j}^{1,1}$ changes with $p$: the larger the value of $p$, the smaller the value of $A_{i,j}^{1,1}$. A smaller $A_{i,j}^{1,1}$ indicates a lower arrival rate of bursts needing to be allocated using WCs and hence a lower burst loss probability. In other words, the calculated burst loss on link $l$ decreases with the relative load difference between the two streams, as described by the streamline effect.

Note that our model is only an approximate one under the truncated Poisson traffic assumption. This is mainly due to the fact that the VCAS scheme at node B in Fig.4.1(b) cannot strictly guarantee that the burst loss at node B equals the total burst loss at nodes A and 1 to N in Fig.4.1(a). VCAS assumes full wavelength conversion capability is available for intra-stream contentions. However, it is not true at node A in Fig.4.1(a).

### 4.4 Simulation Results

In this section, we present simulation results for the 14-node NSFNET network and a 33-node GEANT network [39]. In each network, nodes are connected by two unidirectional links in opposite directions, each with $W$ wavelengths for data burst transmission and one control wavelength channel. Burst lengths follow an exponential distribution with an average value of 10 $\mu s$. There is one flow between each source-destination node pair. The route of each flow is determined using the shortest path algorithm. Input traffic to connections at the ingress nodes follows
the Poisson process. The traffic loads on connections are the same in the case of identical traffic demand and uniformly distributed in the range \([0, 2\rho]\) in the case of non-identical traffic demand. The network load refers to the average load per connection and is measured in Erlangs per wavelength. The conversion ratio in the network refers to the average conversion ratio at the core nodes.

In the simulation experiments, we choose two candidate link models for our proposed algorithm: one is introduced in \([23]\) assuming Poisson arrivals\(^2\) (corresponding results are labelled \textit{Poisson-based allocation} in later figures) and the other is proposed in this paper considering the streamline effect (corresponding results are labelled \textit{SE-based allocation} in later figures). With the same WC allocation algorithm, the more accurate a link model, the better wavelength converters are allocated and the lower the simulation results.

\(^2\)The introduction of this model can be found in Section 5.2.2 in Chapter 5.
4.4.1 Simulations In NSFNET Network

We first show the effectiveness of our proposed WC allocation algorithm by comparing the burst loss probability in the network under it and that under a uniform WC allocation scheme, i.e., each link being equipped with the same number of WCs. Simulation results are shown in Fig. 4.3 (traffic load of 0.5 under identical traffic demand) and Fig. 4.4 (traffic load of 0.5 under non-identical traffic demand). We make three observations from these two figures. First, it can be seen that whichever link model is used, our proposed algorithm can significantly reduce the burst loss probability. Second, the advantage of our proposed algorithm is sustained even when the burst loss probability is relatively high or when the assumption that traffic loads of connections along their routes remain the same is no longer reasonable. Third, in general, there is an improvement in the burst loss performance after the streamline effect is modelled.

The third observation can also be made based on the simulation results shown in Figs. 4.5 to 4.6. Specifically, Figs. 4.5 to 4.6 are for traffic loads of 0.5 and 0.8, respectively, under identical traffic demand; Figs. 4.7 to 4.8 are for traffic loads...
Figure 4.4: Burst loss probability vs. the average number of FWCs per link when the traffic load is 0.5 in the NSFNET network under non-identical traffic demand of 0.5 and 0.8, respectively, under non-identical traffic demand. Each figure shows the burst loss probabilities in the network when the number of wavelengths per link is 8, 16 or 24. As an example, the percentage performance improvement due to the modelling of the streamline effect is shown in Fig. 4.9 (traffic load of 0.5 under the identical traffic demand) and Fig. 4.10 (traffic load of 0.8 under identical traffic demand).

The impact of conversion degree of WCs on the minimum conversion ratio needed for approaching the full wavelength conversion performance is shown in Fig. 4.11, where burst loss probability is plotted against the conversion ratio after WCs are allocated using our proposed WC allocation algorithm and link model when the conversion degree of WCs is 3, 7, 11, 15 or 16 (note that WCs with conversion degree of 16 means they are full-ranged). Other simulation conditions include the number of wavelengths per link being 16 and traffic load being 0.5 under non-identical traffic demand. It can be seen that the best performance achievable strongly depends on the conversion degree of WCs. Only when WCs are nearly full-ranged, the full wavelength conversion performance can be approached.
Figure 4.5: Burst loss probability vs. conversion ratio in the NSFNET network when the traffic load is 0.5 under identical traffic demand

4.4.2 Simulations In GEANT Network

The same set of simulation experiments are carried out in a larger network, i.e., the 33-node GEANT network. Simulation results that compare the effectiveness of our proposed WC allocation algorithm and that of the uniform WC allocation scheme are shown in Fig. 4.12 (traffic load of 0.07 under identical traffic demand) and Fig. 4.13 (traffic load of 0.07 under non-identical traffic demand). Shown in Figs. 4.14 to 4.17 are simulation results demonstrating the minimum wavelength conversion for approaching the full wavelength conversion performance. Specifically, Figs. 4.14 to 4.15 are for traffic loads of 0.07 and 0.1, respectively, under identical traffic demand; Figs. 4.16 to 4.17 for traffic loads of 0.07 and 0.1, respectively, under non-identical traffic demand. The percentage performance improvement due to the modelling of the streamline effect is shown in Fig. 4.18 (traffic load of 0.07 under the identical traffic demand) and Fig. 4.19 (traffic load of 0.1 under the identical traffic demand). The effect of conversion degree of WCs is shown in Fig. 4.20, where the burst loss probability is plotted against the conversion ratio after WCs are allocated using our proposed WC allocation algorithm and link model.
Figure 4.6: Burst loss probability vs. conversion ratio in the NSFNET network when the traffic load is 0.8 under identical traffic demand.

The simulation conditions include that the number of wavelengths per link is 16, traffic load is 0.07 under non-identical traffic demand and the conversion degree of WCs is 3, 7, 11, 15 or 16.

From the simulation results in the GEANT network, we can see the similar tendencies we have observed in the simulation results in the NSFNET network.

4.5 Summary

In this chapter, we have proposed an algorithm to allocate a given number of WCs at the core nodes in an OBS network based on a link model. We have shown the algorithm’s optimality in reducing the burst loss probability under the constant-load assumption. We also have introduced a link model which considers the streamline effect and the dependence among burst arrival processes on the difference wavelengths. Simulation results show that our proposed algorithm can significantly reduce the burst loss probability in an OBS network compared to the uniform WC allocation scheme. Meanwhile, it is shown that modelling the streamline can
Figure 4.7: Burst loss probability vs. conversion ratio in the NSFNET network when the traffic load is 0.5 under non-identical traffic demand improve the performance of the proposed converter allocation algorithm. We also have observed that the conversion degree of WCs should be close to the number of wavelengths per link so that the full wavelength conversion performance can be approached.
Figure 4.8: Burst loss probability vs. conversion ratio in the NSFNET network when the traffic load is 0.8 under non-identical traffic demand

Figure 4.9: Performance improvement after the streamline effect is modelled when the traffic load is 0.5 under the identical traffic demand in the NSFNET network
Figure 4.10: Performance improvement after the streamline effect is modelled when the traffic load is 0.8 under the identical traffic demand in the NSFNET network.

Figure 4.11: Burst loss probability vs. conversion ratio in the NSFNET network when conversion degree of WCs changes.
Figure 4.12: Burst loss probability vs. the average number of FWCs per link when the traffic load is 0.07 in the GEANT network under identical traffic demand.

Figure 4.13: Burst loss probability vs. the average number of FWCs per link when the traffic load is 0.07 in the GEANT network under non-identical traffic demand.
Figure 4.14: Burst loss probability vs. conversion ratio in the GEANT network when the traffic load is 0.07 under identical traffic demand.

Figure 4.15: Burst loss probability vs. conversion ratio in the GEANT network when the traffic load is 0.1 under identical traffic demand.
Figure 4.16: Burst loss probability vs. conversion ratio in the GEANT network when the traffic load is 0.07 under non-identical traffic demand

Figure 4.17: Burst loss probability vs. conversion ratio in the GEANT network when the traffic load is 0.1 under non-identical traffic demand
Figure 4.18: Performance improvement after the streamline effect is modelled when the traffic load is 0.07 under the identical traffic demand in the GEANT network.

Figure 4.19: Performance improvement after the streamline effect is modelled when the traffic load is 0.1 under the identical traffic demand in the GEANT network.
Figure 4.20: Burst loss probability vs. conversion ratio in the GEANT network when conversion capability of WCs changes
Chapter 5

Burst Rescheduling Algorithms

5.1 Introduction

In a partially wavelength-convertible network with limited number of WCs, there exist two kinds of burst losses, namely, non-WC-induced burst loss and WC-induced burst loss. Non-WC-induced burst loss arises when all the wavelengths within the conversion range of WCs are busy when a new burst arrives. WC-induced burst loss occurs when there is no free WC to convert the wavelength of an arriving burst. Both kinds of burst losses should be considered in a burst scheduling algorithm so as to reduce the overall burst loss probability. However, a majority of existing scheduling algorithms have been proposed for fully wavelength-convertible networks without WC-induced burst loss [7][44][45][56]. To reduce non-WC-induced burst loss these algorithms may use WCs to shift bursts to other wavelengths when their original wavelengths are free, thus increasing the possibility of WCs being simultaneously busy and hence WC-induced burst loss.

To decrease WC-induced burst loss, more bursts can be allocated to their incoming wavelengths so that a larger number of WCs are saved for future use. Based on this idea, in CAS, a burst will be allocated to its incoming wavelength if it is free. Otherwise, LAUC-VF is invoked. It is evident that non-WC-induced burst
loss under CAS is higher than that under LAUC-VF since the original wavelengths of bursts may not be the best ones to reduce this kind of burst loss. Nevertheless, simulation results show that CAS can significantly decrease the overall burst loss probability in most situations. This indicates that reducing WC-induced burst loss is key to lowering the overall burst loss when the number of WCs is not large enough to provide full wavelength conversion capability.

In this chapter, we illustrate that WC-induced burst loss can be decreased using burst rescheduling. We also introduce a link model for performance analysis when burst rescheduling is carried out. In a network however, a rescheduled burst may be dropped at the next node on its route due to its changed wavelength, thus increasing the overall burst loss probability. To reduce the loss of rescheduled bursts, we propose two burst rescheduling algorithms, viz., the conservative rescheduling (CR) algorithm and the aggressive rescheduling (AR) algorithm. The proposed algorithms’ effectiveness in reducing the overall burst loss probability, their computational complexity and their signaling overheads are evaluated through simulation experiments.

The chapter is organized as follows. The implementation and benefit of burst rescheduling are explained in Section 5.2. We also introduce a link model in this section. The two proposed burst rescheduling algorithms are presented in Section 5.3. Section 5.4 shows the simulation results. Finally, we conclude in Section 5.5.

5.2 Burst Rescheduling At A Single Node

In this section, we first illustrate the implementation and benefit of burst rescheduling at a single node. A link model is also introduced in this section. We assume in this section and in the sequel that the SPL structure is used at the core nodes, although the implementation of burst rescheduling is independent of the WC deployment structure.
5.2.1 Implementation And Benefit

Consider a node with one WC bank of $C$ WCs on each output link. The number of wavelengths per link is $W$. The conversion ratio is then $\frac{C}{W}$. As in Chapter 4, WCs are circular ones and the conversion degree is denoted as $D_d$. If $D_d \geq W$, a WC is an FWC; otherwise, it is an LWC.

On the output link of the node, reservations for bursts are made on wavelengths under JET. Therefore, the reservation on a wavelength for a burst, say burst $x$, is from its start time $t^s_x$ to its end time $t^e_x$, with $t^s_x$ equal to $t^h_x + T_x$ and $t^e_x$ being $t^h_x + T_x + l_x$, where $l_x$, $t^h_x$ and $T_x$ are burst $x$’s length, header’s arrival time, and the offset time, respectively. If burst $x$ is sent to an FDL to be delayed before being sent to a WC bank, the values of $t^s_x$ and $t^e_x$ increase correspondingly. The processing time of a control packet at a node is $\delta$.

A burst can be rescheduled when three requirements are met. Let burst $x$ be an incoming burst and burst $y$ a burst which has been allocated onto the original wavelength of burst $x$, denoted as $w^o_x$, and overlaps with burst $x$, i.e.,

\begin{align*}
    t^e_y &> t^s_x, \quad (5.1) \\
    t^s_y &< t^e_x. \quad (5.2)
\end{align*}

We call burst $y$ a blocking burst for burst $x$ since it keeps burst $x$ from being allocated onto its original wavelength $w^o_x$. Blocking burst $y$ is the burst to be rescheduled so that incoming burst $x$ can be allocated onto wavelength $w^o_x$. To reschedule burst $y$, the first requirement is that $t^h_x + \delta < t^s_y$, which means that burst $y$ is not yet being transmitted after burst $x$’s header is processed to know its original wavelength $w^o_x$. Otherwise, the assigned wavelength of burst $y$ cannot be adjusted. The second requirement is that there is at least one free wavelength besides wavelength $w^o_x$ to accommodate burst $y$. The last requirement is that burst $y$ is a shifted one, i.e., $w^o_y \neq w^o_x$.

An example of the implementation of burst rescheduling is shown in Fig.5.1,
where WCs are full-ranged. In Figs. 5.1(a) and (b), W=3 and C=1; in Figs.5.1(c) and (d), W ≥ 4 and C ≥ 2. A burst, say burst x, is represented by a triple \((x, w^o_x, w_x)\), where \(x\), \(w^o_x\) and \(w_x\) are its ID, original wavelength and assigned wavelength on the output link, respectively. If \(w^o_x \neq w_x\), a WC is used to convert the wavelength of burst \(x\) from \(w^o_x\) to \(w_x\). A burst’s header is represented using its ID. In Fig.5.1, bursts 1, 2 and 3 overlap with each other. The original wavelengths of the three bursts are wavelengths 1, 1 and 2, respectively. We assume bursts 1 and 2 have been allocated onto wavelengths 1 and 2, respectively, and burst 3 is the incoming burst. Since \(w^o_2 \neq w_2\), a WC is used by burst 2. After allocating burst 3 without bursts rescheduling (i.e., by the CAS algorithm), the reservations on wavelengths are shown in Figs. 5.1(a) and (c). Specifically, burst 3 is dropped in Fig.5.1(a) since the only WC is used by burst 2 and burst 3 cannot access the free wavelength 3. With burst rescheduling, the reservations are shown in Figs.5.1(b) and (d), where burst 2 is rescheduled to wavelength 3 and burst 3 is allocated onto its original wavelength.

The example shows that burst rescheduling can decrease WC-induced burst loss in two ways. First, more bursts are accepted when all WCs are busy, which directly reduces WC-induced burst loss. This is shown in Figs.5.1(a) and (b). Second, more WCs are saved for future use and thus fewer bursts coming later will be dropped due to the lack of free WCs. This is shown in Figs.5.1(c) and (d), where the number of busy WCs decreases from 2 to 1 after burst 2 is rescheduled.

To allocate more bursts to their incoming wavelengths using burst rescheduling, it is desirable, according to the first requirement of burst rescheduling, to decrease the probability that the processing of a burst’s header cannot be finished before the start time of the burst’s blocking burst, which we term transmitting probability and denote as \(P_{tr}\) in this paper. For an incoming burst \(x\) and its blocking burst \(y\), \(P_{tr}\) equals the probability that \(t^*_{y} < t^*_{x,h} + \delta\) or \(t^*_{y} - l_y < t^*_{x} - T_x + \delta\). This indicates that increasing offset \(T_x\) can decrease \(P_{tr}\) and thus allow more bursts to be rescheduled. According to Eq. (5.1), the upper bound on \(P_{tr}\) is the probability that \(l_y > TMIN - \delta\) when \(t^*_{x} - t^*_{y} \to 0\) and \(T_x = TMIN\) where \(TMIN\) is the...
smallest offset time. In particular, $P_{tr}$ is always zero if $T_{MIN} - \delta \geq LAMX$ if there is an upper bound, denoted as $LMAX$, on the burst length.

### 5.2.2 Theoretical Analysis

We introduce an analytical model in this section to estimate the burst loss probability on a link. This model can be used whether burst rescheduling is allowed or not (i.e., by the CAS algorithm). The assumptions include:

- the offset times of all bursts are the same;
- FWCs are used;
- integrated nodes do not exist;
- $P_{tr} = 0$.

With the same offset time, the benefit of burst rescheduling in reducing the overall burst loss probability is likely to increase. The same offset time indicates that the arrival order of headers is the same as that of bursts. As a result, no incoming burst will overlap with voids between existing burst reservations. Otherwise, the start time of an incoming burst will be earlier than that of a burst whose header arrives before the incoming burst’s header, which is impossible when all bursts have the same offset time. Therefore, non-WC-induced burst loss cannot be reduced by decreasing the voids generated. In other words, burst rescheduling will not cause the increase in non-WC-induced burst loss. Consequently, the decrease in the overall burst loss probability due to burst rescheduling increases and equals the decrease in the WC-induced burst loss probability.

With FWCs, the probability of finding a free wavelength for an incoming burst is larger and thus more bursts are allocated to the wavelengths different from their incoming wavelengths. Since only shifted bursts can be rescheduled, this implies that more bursts can be rescheduled and thus a larger reduction in WC-induced
burst loss. Similarly, in the absence of integrated nodes the number of shifted bursts increases since all bursts arriving at core nodes are transit and the contentions among transit bursts can only be resolved by WCs. The condition $P_{tr} = 0$, as explained previously, allows the largest number of bursts to be rescheduled, given other conditions such as the conversion ratio and the number of wavelengths per link.

For the ease of analysis, we assume that there is no FDL at the core nodes. The input traffic to an output link is Poisson and an incoming burst will arrive from any one of the $W$ wavelengths with equal probability. The overall burst arrival rate is $\lambda$ and the average burst length is $\frac{1}{\mu}$. Note that although, as pointed out in the previous two chapters, the Poisson assumption for traffic arrivals is not accurate in the presence of the streamline effect, it allows easy performance analysis. So, it is often used in a link model for purely theoretical analysis as in this chapter\(^1\).

Under these assumptions, the burst loss performance on an output link can be estimated from a two-dimensional Markov chain model. A state $(i, j)$, $0 \leq i \leq W$, $0 \leq j \leq W$, $j \leq i$ and $j \leq C$, in the model denotes that $i$ wavelengths are busy on an output link with $j$ WCs in use. Transition rates in the model can be expressed using parameters defined below for an incoming burst $x$ when the state is $(i, j)$ at time $t_x$.

- $\alpha_{i,j}$: the probability that a blocking burst $y$ exists on wavelength $w_x^o$ and is a shifted one;

- $\nu_{i,j}$: the probability that a blocking burst $y$ exists on wavelength $w_x^o$ and is not a shifted one;

- $\tau_{i,j}$: the probability that a blocking burst $y$ on wavelength $w_x^o$ can be rescheduled if it exists and is a shifted one.

\(^1\)In the previous two chapters, a link model is proposed to be used in an algorithm and therefore impacts the effectiveness of the algorithm.
The values of these parameters are relatively easy to determine under the assumption of the same offset time for all bursts. Under this assumption, an incoming burst $x$’s start time $t_x^s$ is later than any burst reservation’s start time since its header is the latest arriving one. Therefore, a wavelength free at time $t_x^s$ is also free after time $t_x^s$ and thus capable of accommodating burst $x$, which means a blocking burst appears on burst $x$’s original wavelength only when burst $x$ arrives from one of the $i$ wavelengths that are busy at time $t_x^s$. So, we have

$$\alpha_{i,j} = \frac{j}{W},$$
$$\nu_{i,j} = \frac{i-j}{W}.$$  \hspace{1cm} (5.3)  \hspace{1cm} (5.4)

The value of $\tau_{i,j}$ depends on whether rescheduling is allowed. When rescheduling is not allowed, $\tau_{i,j} = 0$ and our proposed model becomes the same as that proposed in [23]. Otherwise, $\tau_{i,j}$ is equal to the probability that at least one wavelength is free from time $t_y^s$ to time $t_y^e$. We first check the wavelengths busy at time $t_x^s$. We know that the header of burst $y$ arrives earlier than that of burst $x$, i.e., $t_y^h < t_x^h$. So, we have $t_y^s < t_x^s$ since the offset time for all bursts is the same. Meanwhile, as bursts $x$ and $y$ overlap with each other, we get $t_y^e > t_x^e$ according to Eq. (5.1). Therefore,

$$t_y^s < t_x^s < t_y^e,$$ \hspace{1cm} (5.5)

which means that wavelengths that are busy at time $t_x^s$ cannot be allocated to burst $y$. Consequently, $\tau_{i,j}$ equals one minus the probability that none of the $W-i$ wavelengths free at time $t_x^s$ can be allocated to burst $y$. We know that a wavelength that is free at time $t_x^s$ is also free after time $t_x^s$. Meanwhile, we consider the likelihood that a short burst reservation exists between time $t_y^s$ and time $t_x^s$ is very small. So, based on Eq. (5.5), we know that a wavelength which is free at time $t_x^s$ can accommodate burst $y$ if and only if it is also free at time $t_y^s$. We

---

Footnote:

2In the link models introduced in the previous two chapters, the assumption of equal offset time for all bursts also applies, which is not explicitly pointed out.
therefore have

\[ \tau_{i,j} = \begin{cases} 
1, & i - 1 < W - i; \\
1 - \frac{i-1}{W-1} - \frac{i-1-(W-i)}{W-1-(W-i)}, & \text{otherwise}; \\
i - 1 \geq W - i, & \end{cases} \] (5.6)

after assuming the number of wavelengths busy at time \( t_x^s \) is equal to that at time \( t_y^s \) based on the fact that \( t_x^s - t_y^s \) is very small.

Using the parameters defined earlier, the transition rates in the model can be expressed below, where \( A_{i,j}^{a,b} \) is the transition rate from state \((i, j)\) to state \((i + a, j + b)\) and equals zero when \( 0 \leq i + a \leq W \) or \( 0 \leq j + b \leq \min(C, i + a) \) is not met.

- \( A_{i,j}^{1,0} = \lambda(1 - \nu_{i,j} - \alpha_{i,j} + \alpha_{i,j}\tau_{i,j}) \): In this case, incoming bursts are allocated onto their original wavelengths. This occurs when their original wavelengths are free. This arrival rate will be \( \lambda(1 - \nu_{i,j} - \alpha_{i,j}) \). This can also occur when the original wavelengths of incoming bursts are busy due to blocking bursts. In this case, with the same offset time for all bursts, there is at most one blocking burst for an incoming burst \( x \) on its original wavelength. Otherwise, these blocking bursts will overlap with each other at time \( t_x^s \) on wavelength \( w_x^o \) according to Eq. (5.5), which is impossible. Therefore, incoming burst \( x \) can be allocated onto its original wavelength if its only blocking burst \( y \) is a shifted one and can be rescheduled. This arrival rate is \( \lambda\alpha_{i,j}\tau_{i,j} \).

- \( A_{i,j}^{1,1} = \lambda(\nu_{i,j} + \alpha_{i,j}(1 - \tau_{i,j})) \): In this case, incoming bursts are allocated onto wavelengths different from their original wavelengths. This arrival rate is equal to \( \lambda - A_{i,j}^{1,0} \) or \( \lambda(\nu_{i,j} + \alpha_{i,j}(1 - \tau_{i,j})) \).

- \( A_{i,j}^{-1,0} = (i - j)\mu \): In this case, a burst is transmitted onto its original wavelength on the output link.

- \( A_{i,j}^{-1,-1} = j\mu \): In this case, a burst is transmitted onto a wavelength different from its original wavelength on the output link.
The steady state probability of state \((i, j)\), denoted as \(\pi_{i,j}\), can be determined by solving the global balance equation (4.12) in Chapter 4.

The overall burst loss probability on the output link can be determined using Eqs. (4.8) and (4.13) in Chapter 4 or directly using below formula:

\[
P_{\text{loss}} = \sum_{i=C}^{W-1} \pi_{i,C}(\nu_{i,j} + \alpha_{i,j}(1 - \tau_{i,j})) + \sum_{j=0}^{C-1} \pi_{W,j}.
\]

The benefit of burst rescheduling in reducing the burst loss probability is then equal to the value of \(P_{\text{loss}}\) when \(\tau_{i,j}\) is zero minus the value of \(P_{\text{loss}}\) when \(\tau_{i,j}\) is calculated using Eq. (5.6).

5.3 Burst Rescheduling In A Network

In this section, burst rescheduling is investigated in a network. We first illustrate two phenomena affecting the performance of burst rescheduling. Following that, two burst rescheduling algorithms are presented.

5.3.1 Two Related Phenomena In A Network

The first phenomenon related to the performance of burst rescheduling is that the offset time of a burst reduces along the route of the burst. The minimum offset time \(T_{\text{min}}\) appears at the last hop of a burst’s route. We know that the smaller the offset time, the larger the transmitting probability \(P_{tr}\) and hence the decrease in WC-induced burst loss reduces after burst rescheduling is applied. Therefore, it is desirable to increase the offset time and thus \(T_{\text{min}}\) if they are not large enough compared to the burst length. To do that, we can introduce a fixed extra offset time at the ingress nodes for each burst. It is noted that the introduction of a
fixed extra offset time will not increase the burst loss. The reason is that neither the arrival order of headers nor that of bursts changes.

The second phenomenon is that a rescheduled burst may be dropped at the next node on its route due to the change of its assigned wavelength. Assume burst \( y \) is rescheduled from wavelength \( w_y \) to wavelength \( w_y^r \) at a node. Also assume the next node \( N_y \) on its route is not its egress node \( E_y \) and a wavelength \( w_y^N \) has been reserved for it on the output link at node \( N_y \). Burst \( y \) will be dropped at node \( N_y \) in the following two cases:

- \( w_y^N = w_y \) and there is no free WC for burst \( y \) at node \( N_y \); or

- \( w_y^N \neq w_y \) and \( w_y^N \) is out of the conversion range of WCs when the input wavelength is \( w_y \).

In the first case, a WC is not reserved for burst \( y \) at node \( N_y \) since \( w_y = w_y^N \). Therefore, when the wavelength of burst \( y \) changes, burst \( y \) will be dropped at node \( N_y \) if there is no free WC. In the second case, burst \( y \) is dropped at node \( N_y \) since it cannot be shifted from wavelength \( w_y^r \) to the previously reserved wavelength \( w_y^N \).

The second phenomenon increases the overall burst loss probability. Therefore, the loss of rescheduled bursts should be considered in a burst rescheduling algorithm. In what follows, we propose two rescheduling algorithms. In both of them, burst rescheduling is considered only when one blocking burst overlaps with an incoming burst. In doing so, the high computational complexity related to rescheduling multiple bursts is avoided. This only affects the benefit of burst rescheduling slightly since the probability of successfully rescheduling multiple bursts is low.
Table 5.1: CR algorithm

**Step 1**: Set \( f = 0 \);

**Step 2**: If current FDL is free, delay the incoming burst \( x \) and try scheduling methods a), b) and c) in sequence. As soon as burst \( x \) is accepted onto a free wavelength, terminate the algorithm.

a) allocate burst \( x \) onto wavelength \( w_x^{o} \) directly if wavelength \( w_x^{o} \) is free;

b) allocate burst \( x \) onto wavelength \( w_x^{o} \) after rescheduling its blocking burst \( y \) using the LAUC-VF algorithm, if

- \( N_y = E_y \); or

- node \( N_y \) is fully wavelength-convertible;

c) allocate burst \( x \) using the LAUC-VF algorithm;

**Step 3**: If \( f = F \), terminate the algorithm; otherwise, \( f = f + 1 \) and go to step 2.
5.3.2 Rescheduling Algorithms

5.3.2.1 Conservative Rescheduling Algorithm

In the conservative rescheduling (CR) algorithm, a burst can be rescheduled in two situations: 1) it is at its last hop; 2) it is not at its last hop but the next node on its route is fully wavelength-convertible. When at its last hop, the burst will be sent to its egress node where it is accepted and electronically processed. In the second case, the burst will not be dropped due to the change of its wavelength since there are always free WCs and each WC is a full-range one at the next node. The algorithm is considered to be conservative since the loss of rescheduled bursts due to their changed wavelengths is avoided completely at the expense of fewer bursts being rescheduled and hence a smaller decrease in WC-induced burst loss. The CR algorithm is presented in Table 5.1, where we assume \( F \) FDLs exist and the \( f \)th FDL can delay a burst by \( f \Delta t \) in time (\( f = 0 \) indicates no FDL is used).

5.3.2.2 Aggressive Rescheduling Algorithm

The framework of the aggressive rescheduling (AR) algorithm, as shown in Table 5.2, is similar to the CR algorithm. The changed part is that one more situation is added for burst rescheduling. In this situation, if burst rescheduling is not carried out, an incoming burst \( x \) will be dropped since its original wavelength is busy and all WCs are used. By rescheduling its blocking burst \( y \) on its original wavelength, burst \( x \) can be accepted. In this situation, burst \( y \) may be dropped at its next node \( N_y \) since \( N_y \) is neither its egress node nor fully wavelength-convertible.

We consider this algorithm is aggressive compared to the CR algorithm since it allows the loss of rescheduled bursts to some degree. Whether the AR algorithm can outperform the CR algorithm needs to be tested through simulation experiments. This is because some bursts may be dropped due to the bandwidth reserved for dropped rescheduled bursts in the AR algorithm, the impact of which on the overall burst loss performance is hard to evaluate theoretically.
Table 5.2: AR algorithm

**Step 1**: Set $f=0$;

**Step 2**: If current FDL is free, delay the incoming burst $x$ and try scheduling methods a), b) and c) in sequence. As soon as burst $x$ is accepted onto a free wavelength, terminate the algorithm.

a) allocate burst $x$ onto wavelength $w^o_x$ directly if wavelength $w^o_x$ is free;

b) allocate burst $x$ onto wavelength $w^o_x$ after rescheduling its blocking burst $y$ using the LAUC-VF algorithm, if

- $N_y = E_y$; or
- node $N_y$ is fully wavelength-convertible; or
- all WCs are busy;

c) allocate burst $x$ using the LAUC-VF algorithm;

**Step 3**: If $f = F$, terminate the algorithm; otherwise, $f=f+1$ and go to step 2.
5.3.3 Signalling Overheads

In both the CR algorithm and the AR algorithm, a NOTIFY packet needs to be generated for each rescheduled burst to inform its next node of its new wavelength. Compared with a header packet, a NOTIFY packet is much shorter since it only carries a wavelength ID besides the burst ID.

5.3.4 Complexity

Assume there are at most $M_w$ voids on a wavelength and they are searched linearly. The worst case computational complexity of the CAS algorithm, the CR algorithm and the AR algorithm for searching a free wavelength is listed as follows.

- the CAS algorithm: $O(WM_w)$, which occurs when the LAUC-VF algorithm is carried out to allocate an incoming burst;
- the CR algorithm: $O(2WM_w)$, which occurs when the LAUC-VF algorithm is carried out twice to allocate an incoming burst $x$: in the first time the LAUC-VF algorithm is carried out to reschedule burst $x$’s blocking burst $y$ so that burst $x$ can be allocated onto its original wavelength; after this fails, the LAUC-VF algorithm is implemented again to allocate burst $x$ without burst rescheduling;
- the AR algorithm: $O(2WM_w)$, which occurs in the way as explained above for the CR algorithm when $N_y = E_y$ or node $N_y$ is fully wavelength-convertible.

We can see that the computational complexity of the CR algorithm and the AR algorithm for searching a free wavelength for a burst is two times higher than that of the CAS algorithm. Meanwhile, the overall computational complexity actually should also include the part for searching a free WC for an incoming burst. For this part, the three algorithms have the same complexity since WCs need to be searched at most one time for each incoming burst. Therefore, the computational
complexity of the CR algorithm and the AR algorithm is in fact less than two times that of the CAS algorithm. The percentages of headers processed with the worst case complexity in the CR algorithm and the AR algorithm are investigated in the next section.

5.4 Simulation Results

We conduct simulation experiments at a node with a single output link and in a whole network. The goal of the simulation at a node is to show the potential benefit of burst rescheduling in reducing the burst loss probability. The agreement between simulation results and theoretical estimates is also examined. Our emphasis is on the simulation experiments in a network, which are carried out 1) to evaluate the performance of the CR algorithm and the AR algorithm in terms of their capabilities to decrease the burst loss probability and 2) to investigate the signalling overheads and complexity of the two algorithms. In the simulation, the traffic load unit is Erlang per wavelength. Besides, we assume:

- the number of wavelengths for data burst transmission is 16 on one (unidirectional) link;
- there is one control wavelength channel on each link;
- the average burst length is $10\mu s$.

In the analysis of the simulation results, the performance advantage of one algorithm, say the CR algorithm, over the other algorithm, say the CAS algorithm, is evaluated using $(P_{\text{loss}}^{\text{CAS}} - P_{\text{loss}}^{\text{CR}})/P_{\text{loss}}^{\text{CAS}}$, where $P_{\text{loss}}$ represents the burst loss probability.
5.4.1 Simulation Study At A Single Node

In this experiment, traffic generated at edge nodes is Poisson and the traffic load is 0.5. We assume that burst lengths follow either a uniform distribution or an exponential distribution\(^3\). In the case of the uniform distribution, the maximum burst length and the burst offset time are both 20\(\mu s\) so that \(P_{tr}=0\). In the case of the exponential distribution, the offset time is three times the average burst length so that \(P_{tr}\) is 5%. Using the same offset time for all bursts leads to non-WC-induced burst loss to be always minimized. Hence, the overall burst loss reduction due to burst rescheduling is equal to the decrease in WC-induced burst loss. Besides, FWCs are assumed.

Simulation results are shown in Fig. 5.2, where burst loss probability is plotted against the number of WCs when burst rescheduling is and is not allowed (i.e., by the CAS algorithm). It is indicated that burst rescheduling has the potential to improve the burst loss performance significantly. The benefit of burst rescheduling is most obvious when the conversion ratio is medium. Specifically, the performance improvement due to burst rescheduling is between 45% and 70% when the number of WCs is within the range from 4 to 11 or conversion ratio varies between 25% and 69%. Beyond this range, the improvement is not so obvious. There are two reasons for this. First, when the conversion ratio nears one, WC-induced burst loss is already trivial and hence there is less room to decrease it. Second, when the conversion ratio is close to zero, only a few bursts can be rescheduled since the number of shifted bursts decreases dramatically. Fig. 5.2 also demonstrates that the theoretical estimates are close to the simulation results. Moreover, it shows that when \(P_{tr}\) is small enough, the largest benefit of burst rescheduling in decreasing the burst loss probability can be approached.

\(^3\)We can assume arbitrary burst length distribution since it is not specified in the link model which does not involve queues. This is similar to the ErlangB formula, which is also applicable to a queueless system with arbitrary distribution of service time [78]
5.4.2 Simulation Study In The Network

Simulation experiments are conducted in the NSFNET network, within which nodes are connected by two unidirectional links in opposite directions. We assume the core nodes do not function as the edge nodes, i.e., we consider the edge/core network defined in Chapter 3. There is one flow (or connection) between each source-destination node pair. The traffic loads on connections are the same under identical traffic demand and follow a uniform distribution in the range $[0, 2\rho]$ under non-identical traffic demand, where $\rho$ is the average traffic load per flow. The route of each flow is determined using the shortest path algorithm. Within each flow, two offset time based QoS classes with equal load are assumed. The value of the class-related extra offset time is $20\mu s$ for class-1 bursts and is zero for class-2 bursts at edge nodes. So, class-1 traffic has a higher priority. Traffic generated at ingress nodes is Poisson. Burst lengths are uniformly distributed in the range $[0\mu s, 20\mu s]$. The rescheduling-related extra offset time is $20\mu s$ to have $P_{tr} = 0$. At one node in the network, if FDLs are equipped, they are shared by all the output wavelengths of the node and the delay provided by the $f$th FDL is $5f\mu s$. The number of wavelengths within an FDL is equal to the number of wavelengths per link.

Two sets of experiments are carried out. The first set of experiments aim at evaluating the burst loss performance under different burst scheduling algorithms when the average number of WCs per WC bank (i.e., per link), number of FDLs per node, the conversion degree of WCs, or the average traffic load per flow changes. The performance of the CR algorithm and the AR algorithm is compared with that of the CAS algorithm. In the second set of experiments, the signalling overheads and complexity of the CR and AR algorithms are investigated.

In these experiments, we assume that the numbers of WCs within WC banks follow a uniform distribution in the range $[0, 2C]$, where $C$ is the average number of WCs per WC bank. Unless otherwise stated, $C$ is 8 or the average conversion ratio in the network is 0.5, WCs are full-ranged, the average traffic load per flow
is 0.5 and no FDL exists.

5.4.2.1 Burst Loss Performance

In Figs. 5.3 (under identical traffic demand) and 5.5 (under non-identical traffic demand), the overall burst loss probability is plotted against the average traffic load per flow. The burst loss probabilities of class-1 and class-2 traffics are presented in Figs. 5.4 (under identical traffic demand) and 5.6 (under non-identical traffic demand). We make two observations from these figures. First, the two burst rescheduling algorithms can outperform the CAS algorithm. Quantitatively, the maximum advantage over the CAS algorithm is 1) 23% under identical traffic demand and 34% under non-identical traffic demand for the CR algorithm, and 2) 27% under identical traffic demand and 39% under non-identical traffic demand for the AR algorithm. Second, the AR algorithm performs better than the CR algorithm, which can also be observed in later experimental results. This suggests that the acceptance of bursts that otherwise will be dropped due to the unavailability of free WCs in the AR algorithm is beneficial in reducing the overall burst loss probability, even if in this case rescheduled bursts may be dropped at downstream nodes.

Simulation results against the number of FDLs per node and the conversion degree of WCs are presented in Figs. 5.7 to 5.10. In Figs. 5.7 (under identical traffic demand) and 5.8 (under non-identical traffic demand), the overall burst loss probability is plotted against the number of FDLs per node. These figures show that the CR algorithm and the AR algorithm can still outperform the CAS algorithm when FDLs exist. In Figs. 5.9 (under identical traffic demand) and 5.10 (under non-identical traffic demand), the overall burst loss probability is plotted against the conversion degree of WCs. These figures show that the performance advantage of either the CR algorithm or the AR algorithm over the CAS algorithm increases with the conversion degree of a WC. The advantage changes 1) from 2% to 23% for the CR algorithm and from 3% to 27% for the AR algorithm under
identical traffic demand, and 2) from 2% to 34% for the CR algorithm and from 4% to 39% for the AR algorithm under non-identical traffic demand. This is because, as explained in Section 5.2.2, the number of shifted bursts increases with the degree of WCs, which allows more bursts to be rescheduled.

In the simulation experiments, we also observe that the CR and the AR algorithms may be outperformed by the CAS algorithm when the full wavelength conversion performance is approached. As an example, the overall burst loss probabilities under different scheduling algorithms are plotted against the number of WCs per WC bank in Fig. 5.11, when WCs are allocated using the algorithm proposed in Chapter 4 and the traffic demand is non-identical. It shows that the maximum performance advantages of the AR algorithm and the CR algorithm over the CAS algorithm can reach up to 45% and 40% in this case, respectively. However, when the full wavelength conversion performance is approached\(^4\), the CAS algorithm performs a little better than the two rescheduling algorithms. This is because non-WC-induced burst loss dominates overall burst loss in this situation. As a result, when more bursts are allocated onto their original wavelengths, which may not be the best choice for reducing non-WC-induced burst loss, the overall burst loss probability becomes larger. So, it is desirable to switch between different algorithms to pursue the lowest overall burst loss probability when the burst loss situation in the network changes. The design of such a switching mechanism can be a topic for future studies and is explained in Chapter 6.

5.4.2.2 Complexity and Signalling Overhead

We investigate the complexity and signalling overheads of the CR and the AR algorithms when WCs are full-ranged. By the analysis in Sections 5.2.2, more bursts are rescheduled in this case. Therefore, more bursts are processed with the worst case computational complexity which occurs when the scheduling of a burst

\(^4\)Due to the optimality of the WC allocation, fewer WCs are needed in this case to approach the full wavelength conversion performance.
involves burst rescheduling. In addition, more bursts being rescheduled also implies more NOTIFY packets are generated, resulting in a larger signalling overhead. The average conversion ratio at the core nodes is 0.5, which is medium and indicates a large benefit of burst rescheduling in reducing the overall burst loss probability according to previous simulation results and analysis.

The percentages of headers processed with the worst case complexity in the CR algorithm and the AR algorithm are plotted against the average traffic load per flow in Figs. 5.12 (under identical traffic demand) and 5.13 (under non-identical traffic demand). It is shown that the maximum percentages with the AR algorithm and the CR algorithm are only 1.5% and 1.0%, respectively, under identical traffic demand and 1.7% and 1.1%, respectively, under non-identical traffic demand. So, the average complexity of the CR algorithm and the AR algorithm is similar to that of the CAS algorithm.

The increase in signalling overheads in the CR algorithm and the AR algorithm is evaluated using the ratio of the number of NOTIFY packets to the total number of headers. This ratio is plotted against the average traffic load per flow in Figs. 5.14 (under identical traffic demand) and 5.15 (under non-identical traffic demand). It is shown that at most 3.3% and 2.7% more signalling overheads are introduced in the AR algorithm and the CR algorithm, respectively, under identical traffic demand and 3.4% and 2.8% more overheads, respectively, under non-identical traffic demand. Considering that the length of a NOTIFY packet is much shorter than a header packet, the increased signalling overheads are even lower. Therefore, the signalling overheads in the CR algorithm and the AR algorithm are close to that in the CAS algorithm.

5.5 Summary

In this chapter, we have studied burst rescheduling in OBS networks with partial wavelength conversion capability. The aim of burst rescheduling is to reduce
WC-induced burst loss and eventually to cut down on the overall burst loss probability. We have shown that burst rescheduling can minimize WC-induced burst loss at a single node. Considering that a rescheduled burst may be dropped at the next node on its route due to its changed wavelength, we have proposed two burst rescheduling algorithms, namely, the CR algorithm and the AR algorithm, in a network. Simulation results have shown that both algorithms can significantly outperform the CAS algorithm before the full wavelength conversion performance is approached. In particular, the AR algorithm performs better than the CR algorithm. Simulation results have also shown that the two burst rescheduling algorithms and the CAS algorithm incur similar overheads and average computational complexity when burst rescheduling can significantly reduce the overall burst loss probability.
Figure 5.1: Comparison between burst allocations without and with burst rescheduling (a) burst allocation without burst rescheduling when $W = 3$ and $C = 1$; (b) burst allocation with burst rescheduling when $W = 3$ and $C = 1$; (c) burst allocation without burst rescheduling when $W \geq 4$ and $C \geq 2$; (d) burst allocation with burst rescheduling when $W \geq 4$ and $C \geq 2$. 
Figure 5.2: Overall burst loss probability vs. number of WCs per WC bank at a single node

Figure 5.3: Overall burst loss probability vs. average traffic load per flow under identical traffic demand
Figure 5.4: Burst loss probability vs. average traffic load per flow for traffic of different classes under identical traffic demand

Figure 5.5: Overall burst loss probability vs. average traffic load per flow under non-identical traffic demand
Figure 5.6: Burst loss probability vs. average traffic load per flow for traffic of different classes under non-identical traffic demand

Figure 5.7: Overall burst loss probability vs. the number of FDLs per node under identical traffic demand
Figure 5.8: Overall burst loss probability vs. the number of FDLs per node under non-identical traffic demand

Figure 5.9: Overall burst loss probability vs. the conversion degree of WCs under identical traffic demand
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Figure 5.10: Overall burst loss probability vs. the conversion degree of WCs under non-identical traffic demand

Figure 5.11: Overall burst loss probability vs. the average number of WCs per WC bank under non-identical traffic demand
Figure 5.12: Percentage of headers processed with the worst case complexity vs. average traffic load per flow under identical traffic demand

Figure 5.13: Percentage of headers processed with the worst case complexity vs. average traffic load per flow under non-identical traffic demand
Figure 5.14: Increased signalling overhead vs. average traffic load per flow under identical traffic demand

Figure 5.15: Increased signalling overhead vs. average traffic load per flow under non-identical traffic demand
Chapter 6

Conclusion

6.1 Research Contribution

The assumption of non-full wavelength conversion capability in OBS networks is more reasonable compared with the full wavelength conversion assumption in light of the fact the WCs are expensive and still immature technologically in the foreseeable future. However, the non-full wavelength-conversion assumption indicates a lower capability of using WCs to resolve contentions among bursts for output wavelengths. As a result, QoS enhancement becomes more important. In this thesis, we have proposed several QoS enhancement approaches in non-fully wavelength-convertible OBS networks.

In Chapter 3, we have proposed an offline wavelength assignment scheme in non-wavelength-convertible OBS networks. In this approach, the WSO of a connection is formed by sorting wavelengths in decreasing order of their priorities, which are determined based on calculated burst loss probabilities on the different wavelengths along a connection’s route: the lower the calculated burst loss probability on a wavelength, the higher the priority of the wavelength. This way, more traffic is transmitted to wavelengths with fewer contentions among bursts. The burst loss probability on a wavelength along a connection’s route is calculated based on a
link model considering the streamline effect, i.e., the impact of the relative traffic load difference among the input streams on the burst loss performance on output wavelength channels. Simulation results have shown that the proposed scheme can improve the burst loss performance in the network dramatically compared with existing schemes due to both its adopted link model and its capability of using the complete set of WSOs. Simulation results also have illustrated that the performance of our scheme can be enhanced when the number of wavelengths per link increases and the allowed delay bound for the scheduling of bursts is prolonged.

In Chapter 4, we have studied the WC allocation problem in OBS networks. The aim of WC allocation is to minimize the burst loss probability given the overall number of WCs and the WC deployment structure within the core nodes. We have formulated the WC allocation problem in an OBS network as an integer programming problem and proposed an algorithm accordingly. The key idea of the algorithm is to remove the WCs one by one from an OBS network with full wavelength conversion capability, each time causing the least increase in network-wide burst loss. The burst loss change in the network after a WC is removed is estimated using a link model. We have proven that this scheme is optimal in reducing network-wide burst loss under the constant-load assumption. Simulation results have shown our proposed algorithm can significantly reduce the burst loss probability in an OBS network compared to the uniform WC allocation scheme. Meanwhile, it is shown that modelling the streamline effect can improve the performance of the proposed converter allocation algorithm. We also have observed that the full wavelength conversion performance can be approached only when the conversion degree of WCs is close to the number of wavelengths per link.

In Chapter 5, we have proposed using burst rescheduling to reduce WC-induced burst loss and hence overall burst loss in partially wavelength-convertible OBS networks with non-zero WC-induced burst loss. We have illustrated that WC-induced burst loss can be minimized at a single node using burst rescheduling. We also have introduced a link model to show theoretically the benefit of burst rescheduling in reducing the WC-induced and the overall burst loss probabilities at a node. In a
network however, a rescheduled burst may be dropped at the next node on its route due to its changed wavelength, thus increasing the overall burst loss probability. To reduce the loss of rescheduled bursts, two burst rescheduling algorithms, viz., the CR algorithm and the AR algorithm, have been proposed. In the CR algorithm, the loss of rescheduled bursts is avoided completely by only rescheduling bursts which will not be dropped at subsequent nodes. In the AR algorithm, bursts are also rescheduled if otherwise they will be dropped due to the unavailability of free WCs. The performance of these two rescheduling algorithms is compared with that of the CAS algorithm. Simulation results have shown that both algorithms can significantly outperform the CAS algorithm before the full wavelength conversion performance is approached. Meanwhile, simulation results have also shown that the two burst rescheduling algorithms and the CAS algorithm have similar overheads and average computational complexity when burst rescheduling can significantly reduce the overall burst loss probability.

6.2 Future Work

6.2.1 More Accurate Link Model

Our proposed offline wavelength assignment scheme and WC allocation algorithm are both based on a link model for estimating the burst loss performance on an output link. Simulation results have shown that the accuracy of a link model can help improve the effectiveness of these schemes in reducing burst loss in the network. However, it is difficult to do accurate burst loss performance estimation in OBS networks with non-zero WC-induced burst loss. As a result, the existing link models (including the ones proposed in this thesis) are introduced under certain assumptions that can simply the performance analysis on a link. Such assumptions include, for instance, the same offset time for bursts and the absence of FDLs. As future work, more accurate link models can be introduced without these assumptions.
6.2.2 WC Allocation under Reduced Load Assumption

In this thesis, we have proven our proposed WC allocation algorithm is optimal under the assumption that the traffic loads of connections remain the same along their routes. As future work, we can study the WC allocation problem considering the reduced load of connections along their paths. This will improve the efficiency of the algorithm in reducing the burst loss probability.

6.2.3 Optimal Burst Scheduling

In burst scheduling in partially wavelength convertible OBS networks with non-zero WC-induced burst loss, minimizing WC-induced burst loss is in contradiction with minimizing non-WC-induced burst loss. The reason is that the former generally requires a burst to be allocated to its original wavelength, which may not be the optimal one to reduce non-WC-induced burst loss. Therefore, theoretically, there exists an optimal burst scheduling algorithm to minimize the overall burst loss rather than only one type of burst loss. To design an optimal burst scheduling algorithm, factors that can affect WC-induced burst loss and non-WC-induced burst loss should be considered. Such factors include, for example, the offset time distribution at a node and wavelength conversion capability in the network.

6.2.4 Non-Poisson Assumption in Wavelength Assignment

In the work of wavelength assignment, we assume that the locally generated traffic follows Poisson process and carry out the simulation under the same assumption. As future work, the wavelength assignment problem can be studied with non-Poisson assumption.
6.2.5 Performance Benchmarking in Wavelength Assignment

As future work, the optimal solutions can be ascertained to benchmark the performance of the proposed wavelength assignment algorithm at least for simple scenarios wherein there are only a few wavelengths per link and a small number of nodes in the network.
Publication


Bibliography


[62] B. Zhou, M. Bassiouni and G. Li, “Routing and wavelength assignment in optical networks using logical link representation and efficient bitwise compu-


