Distributed wavelength provisioning in WDM optical networks

Liu, Jian

2009

Liu, J. (2009). Distributed wavelength provisioning in WDM optical networks. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/47048>

<https://doi.org/10.32657/10356/47048>

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**DISTRIBUTED WAVELENGTH PROVISIONING IN WDM
OPTICAL NETWORKS**

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School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

2009

Statement of Originality

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

28/05/2009
Date

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ACKNOWLEDGEMENT

First of all, I would like to thank my supervisor, Dr Xiao Gaoxi, for his continuous support, guidance and encouragement. I enjoy each discussion with him. He always shares his fruitful experiences and knowledge with me. During my study in Nanyang Technological University, Dr Xiao Gaoxi let me know how to do research, how to keep enthusiasm, dedication to excellence, and careful attention to details. I feel very proud to be given this opportunity to study under his supervision. Without his help, this thesis would not have been made.

I wish to express my sincere gratitude to Dr Shum Ping, Director of Network Technology Research Center, and all the members of this family-like center for the wonderful time we shared together and great help from all my officemates.

I would like to thank Dr Tang Ming, Dr Fu Songnian, Dr Zhang Jing, Dr Liu Hairong, Dr Yan Min, Dr Li Yi, Dr Yu Xia, Dr Liu Ning and Dr Chen Bin for their friendship and advice.

I am grateful to all my friends who gave me great support during my difficult time and I am sorry for not putting a quite long name list here.

Finally, I would like to dedicate this thesis to my beloved wife and son, my parents and brother, who are always together with me and giving me incredible love and support.

CONTENTS

Acknowledgement	i
Contents	ii
Summary	iv
List of Abbreviations	vii
List of Figures	viii
List of Tables	x
Chapter 1: Introduction	1
1. 1 Background	1
1. 2 Motivations	2
1. 3 Contributions of the Thesis	4
1. 4 Thesis Outline	5
Chapter 2: Literature Survey	7
2. 1 Lightpath Establishment Problem	7
2. 2 Distributed DLE	12
2. 3 Outdated Link-State Information: Effects and Control	16
2. 3. 1 Effects of the Outdated Link-State Information	16
2. 3. 2 Solutions	16
2. 4 Control Plane	18
2. 4. 1 Routing Protocol	19
2. 4. 2 Signaling Protocol	19
2. 5 Hardware Implementations	20
2. 5. 1 OXC Technologies	20
2. 5. 2 Wavelength Conversion	22
2. 6 Summary	24
Chapter 3: Evaluation and Analysis of Distributed Parallel Reservations	25
3. 1 Introduction	25
3. 2 Multi-Path Parallel Reservation Schemes	27
3. 2. 1 Framework of the Multi-Path Parallel Reservation Method	27
3. 2. 2 Several Specific MPPR Schemes	29
3. 3 An Analytical Model	30
3. 3. 1 Previous Work	31
3. 3. 2 Analytical Models of Parallel Reservation Schemes	32
3. 4 Numerical Results and Discussions	46
3. 4. 1 Evaluations of the Blocking Performance	48
3. 4. 2 Accuracy of Proposed Analytical Model	52
3. 4. 3 Evaluations of the Control Overhead	61

3. 5	Conclusions.....	63
Chapter 4: Performance Evaluations of Distributed Lightpath Provisioning with Dynamic Routing and Wavelength Assignment.....		
4. 1	Introduction.....	64
4. 2	Distributed Lightpath Provisioning with Dynamic RWA.....	65
4. 3	Simulation Results and Discussions	68
4. 3. 1	Comparisons Between the DLP-D Schemes and the Flooding-Only Schemes	71
4. 3. 2	Comparisons Between Different RWA Algorithms Within the DLP-D Framework	77
4. 4	Conclusions.....	87
Chapter 5: Efficient Wavelength Assignment Methods for Distributed Lightpath Restorations.....		
5. 1	Introduction.....	89
5. 2	The Proposed Methods	93
5.2.1	The Framework of the Predefined Sequential Search (PSS) Schemes	94
5.2.2	The Two Proposed Methods	95
5. 3	Theoretical Analysis	99
5. 4	Numerical Simulations and Discussions.....	105
5.5	Conclusions.....	113
Chapter 6: Conclusions		
6. 1	Summary of Main Contributions	115
6. 2	Future Research Directions.....	117
Author's Publications.....		119
BIBLIOGRAPHY		120

SUMMARY

In recent years, wavelength-division multiplexing (WDM) has been gaining acceptance as an effective solution for handling the tremendous bandwidth demands. Wavelength-routed networks promise to become the next-generation optical networks by providing end-to-end transparency. With the developments of wavelength-routed networks, distributed lightpath provisioning becomes an increasingly important research topic since it provides the flexibility and high bandwidth efficiency requested by the future data communications. A critical problem in distributed lightpath provisioning, however, is the unavoidable existence of outdated link-state information: invalid routing and wavelength assignment (RWA) decisions may be made based on the stale link-state information and consequently the lightpath establishment requests may have to be rejected.

In this project, we focus on evaluating and overcoming the effects of outdated link-state information in distributed lightpath provisioning. In Chapter 3, we propose and study the performance of several different methods within a new framework called multipath parallel reservations (MPPR). In such methods, multiple parallel reservation operations can be carried out for setting up a connection between source-destination nodes, so that the impacts of the outdated link-state information are reduced. General yet accurate analytical models are developed. Analytical and simulation results confirm that the network blocking performance can be drastically improved by properly utilizing such methods, especially under light traffic loads with short durations of connections.

We then present the first in-depth study on the benefits of combining low-frequency global link-state information flooding *and* upon-request local information exchanges. Extensive simulation results in Chapter 4 show that the proposed schemes steadily outperform the existing schemes with only global flooding or only local information exchanges. More significantly, we also evaluate the impacts of various factors on the proposed schemes, including RWA algorithm, network topology, number of wavelengths per fiber, global flooding interval and traffic load etc. Such evaluations help to achieve some insights useful for the developments of future lightpath provisioning schemes.

Finally, we study the developments of efficient wavelength assignment schemes for distributed lightpath provisioning. We propose a new framework where each connection request is assigned a wavelength searching sequence. When there is at least one free wavelength along the route, the connection request is assigned the first available wavelength in its searching sequence. By properly assigning different requests with different searching sequences, the blocking caused by outdated link-state information can be significantly lowered. By using the difficult case of distributed lightpath restoration as a case study, we propose and evaluate two different methods within the framework. Theoretical analysis confirms the optimality of the proposed methods in some special cases while for a few important more general cases, it is shown that no method within the framework can guarantee the optimality. In other words, the best wavelength assignment method is link state dependent. Though the optimality of the proposed methods cannot be guaranteed, simulation results show that they significantly outperform the existing ones. For different cases where the original lightpath establishment adopts random and first-fit wavelength assignments

respectively, we discuss the different concerns in developing efficient wavelength assignment methods for distributed restoration.

LIST OF ABBREVIATIONS

Abbreviations

AP	Alternative Path
CR-LDP	Constraint-Based Label Distribution Protocol
DIR	Destination-initiated Reservation
DLE	Dynamic Lightpath Establishment
DLP-D	Distributed Lightpath Provisioning schemes with Dynamic RWA
DSP	Dynamic Shortest-Path
FBXC	Forward Before XC
FCFS	First-Come-First-Serve
FS	Flagged Search
FSP	Fixed Shortest-Path
GMPLS	Generalized Multiple Protocol Label Switching
IETF	Internet Engineering Task Force
IIR	Intermediate-node initiated reservation
ILP	Integer Linear Program
ITU-T	International Telecommunication Union-Telecommunication Standardization Sector
LCP	Least-Congested-Path
MEMS	Micro-Electro-Mechanical Systems
MPPR	Multi Path Parallel Reservations
OBS	Optical Burst Switching
OEO	Optic-Electro-Optic
OIF	Optical Internetworking Forum
OPS	Optical Packet Switching
OSPF-TE	Open Shortest Path First with Traffic Engineering
OXC	Optical Cross-Connects
PS	Periodical Search
PSS	Predefined Sequential Search
QoS	Quality-of-Service
RWA	Routing and Wavelength Assignment
SIR	Source-Initiated Reservation
SLE	Static Lightpath Establishment
SOA	Semiconductor Optical Amplifier
WDM	Wavelength-Division Multiplexing
WROBS	Wavelength-Routed Optical Burst-Switched

LIST OF FIGURES

Fig. 2. 1: A logical architecture of an OXC.....	21
Fig. 2. 2: An example of an optoelectronic wavelength converter.	22
Fig. 2. 3: An example of an all-optical wavelength converter.....	23
Fig. 3. 1: An example of MPPR scheme where we have two candidate routes and one reservation on each route (i.e., the 2P-2R scheme).....	28
Fig. 3. 2: The birth-death process of different link states in wavelength-routed networks with distributed parallel reservations.	37
Fig. 3. 3: Topology of PacNet.....	47
Fig. 3. 4: Blocking performance of the different parallel reservations schemes under traffic with an average duration of each connection of 100ms.	49
Fig. 3. 5: Blocking performance of different parallel reservations schemes under traffic loads with an average duration of each connection of 1000s.....	51
Fig. 3. 6: Accuracy of the analytical models in PacNet under short-duration traffic with an average duration of connection of 100 ms.	53
Fig. 3. 7: Accuracy of the analytical models in 12-node ring under short-duration traffic with an average duration of connection of 100 ms.	54
Fig. 3. 8: Accuracy of the analytical models in PacNet under long-duration traffic with an average duration of connection of 1000 s.	55
Fig. 3. 9: Accuracy of the analytical models in 12-node ring under long-duration traffic with an average duration of connection of 1000 s.	56
Fig. 3. 10: Accuracy of the analytical models in PacNet under extra short-duration traffic with an average duration of connection of 10 ms.	57
Fig. 3. 11: Accuracy of the analytical models in PacNet under short-duration traffic with an average duration of connection of 100 ms. There are 16 wavelengths in each fiber.....	59
Fig. 3. 12: Accuracy of the analytical models in 12-node ring under short-duration traffic with an average duration of connection of 100 ms. There are 16 wavelengths in each fiber.....	60
Fig. 3. 13: The average number of control messages processed every second in PacNet under traffic with an average duration of connection of 100 ms.	62
Fig. 3. 14: The average number of control messages processed every second for 2P-2R in PacNet under traffic with different average durations of connection.	62
Fig. 4. 1: Comparisons between the DLP-D and flooding-only schemes adopting the FSP routing method and random wavelength assignment. There are eight wavelengths per fiber.....	72
Fig. 4. 2: Comparisons between the DLP-D and flooding-only schemes adopting the DSP routing method and random wavelength assignment. There are eight wavelengths per fiber.....	73
Fig. 4. 3: Comparisons between the DLP-D and flooding-only schemes adopting the FSP routing method and random wavelength assignment. There are 32 wavelengths per fiber.....	75

Fig. 4. 4: Comparisons between the DLP-D and flooding-only schemes adopting the DSP routing method and random wavelength assignment. There are 32 wavelengths per fiber.....	76
Fig. 4. 5: Comparisons between different RWA methods where there are eight wavelengths per fiber and the flooding interval is 1 second.....	78
Fig. 4. 6: Comparisons between different RWA methods where there are 32 wavelengths per fiber and the flooding interval is 1 second.....	79
Fig. 4. 7: Comparisons between different RWA methods where there are 32 wavelengths per fiber and the flooding interval is 10 seconds.	81
Fig. 4. 8: Comparisons between different RWA methods where there are eight wavelengths per fiber and the flooding interval is 100 seconds.	82
Fig. 4. 9: Comparisons between different RWA methods where there are 32 wavelengths per fiber and the flooding interval is 100 seconds.	83
Fig. 4. 10: Comparisons between different RWA methods where there are eight wavelengths per fiber and the flooding interval is 500 seconds.	85
Fig. 4. 11: Comparisons between different RWA methods where there are 32 wavelengths per fiber and the flooding interval is 500 seconds.	86
Fig. 5 1: A simple example of having a blind contention on the link from node 2 to node 3.....	92
Fig. 5 2: Restoration blocking probability in PacNet, while the original lightpath establishment has adopted random wavelength assignment.....	108
Fig. 5 3: Restoration blocking probability in the 12-node ring network, while the original lightpath establishment has adopted random wavelength assignment.	108
Fig. 5 4: Restoration blocking probability in the 4×4 mesh-torus network, while the original lightpath establishment has adopted random wavelength assignment.	109
Fig. 5 5: Restoration blocking probability in PacNet, while the original lightpath establishment has adopted the first-fit wavelength assignment.	112
Fig. 5 6: Restoration blocking probability in the 12-node ring network while the original lightpath establishment has adopted the first-fit wavelength assignment.	112
Fig. 5 7: Restoration blocking probability in the 4×4 mesh-torus network, while the original lightpath establishment has adopted the first-fit wavelength assignment.	113

LIST OF TABLES

Table 5. 1: Calculation results for the case with two restoration requests, assuming $\{\alpha_{1,1}, \alpha_{1,2}\} = \{0.01, 0.9\}$ and $\{\alpha_{2,1}, \alpha_{2,2}\} = \{0.02, 0.8\}$ 104

Table 5. 2: Optimal solutions for example cases with three restoration requests and random wavelength assignment in lightpath establishment..... 104

1 Introduction

1.1 Background

With the developments of optical communication technology, optical networks have provided a critical and viable platform for global telecommunications and information exchanges. To meet the exponentially growing traffic demands in the Internet, *wavelength-division multiplexing* (WDM) networks have been widely deployed in the last decade. Recently WDM technology is playing a critical role in handling the tremendous bandwidth demands imposed on backbone metro and long haul networks. Based on today's technology, a total of more than 1 Tb/s capacity can be supported in a single optical fiber.

The majority of the WDM networks in the foreseeable near future probably will be *wavelength-routed networks*, where network nodes communicate with each other via end-to-end all-optical connections known as *lightpaths* [1, 2]. The procedure of establishing such connections is called *lightpath provisioning*. In the absence of wavelength conversion, the same wavelength must be used on every hop along the route, known as the *wavelength-continuity constraint* [1]. Compared with the point-to-point WDM links, wavelength-routed networks enjoy much better flexibility and scalability.

Chapter 1

There have also been extensive researches on optical communications in other forms rather than setting up an end-to-end lightpath between each pair of source-destination nodes. The most noticeable work includes Optical Packet Switching (OPS) [3] and Optical Burst Switching (OBS) [4] technologies, which transmit information in IP packets or in a collection of packets called an optical burst, respectively. Due to the serious limits still existing in photonic technologies, however, it is widely believed that these solutions most likely would not be able to replace lightpath-based communications to become the mainstream solution of optical communications in any foreseeable nearly future.

In our project, we focus on studying lightpath communications in WDM optical networks.

1.2 Motivations

Traditional backbone optical networks generally provide static lightpath provisioning where a lightpath, once established, is expected to remain for a long time. For the next-generation optical networks under dynamic traffic loads, however, lightpaths may have to be set up and torn down much more frequently. In the extreme case such as the *wavelength-routed optical burst-switched* (WROBS) networks [5] for example, it is expected that the duration of each lightpath will be at the sub-second scale, thus imposing serious challenges on dynamic lightpath provisioning.

The control of dynamic lightpath provisioning in WDM networks can be either *centralized* or *distributed*. Centralized control helps to achieve efficient utilizations of network resources in small- or medium-size networks with highly static traffic loads. In large networks or networks with highly dynamic traffic loads, however, the central

Introduction

controller responsible for collecting all the information and making all the decisions may be overloaded. In addition, the collections of network-status information and the distributions of control messages in both directions between the controller and the network nodes may take prohibitively long time. Unlike centralized control, distributed lightpath provisioning allows each node in the network to make its own decisions based on the information it has. To facilitate the decision making, link-state information is usually collected, either by global information flooding [6-9] or by local information exchanges between neighborhood nodes [10].

A critical challenge in distributed lightpath provisioning is the unavoidable existence of *outdated* link-state information, either because link-state information is exchanged only periodically or upon being triggered [11, 12], or due to the propagation delay along the links [13, 14]. Due to the outdated link-state information they have, several lightpath provisioning requests may conflict against each other trying to reserve the same wavelength on the same link, while there are still plenty of idle capacities on the link. Similar problem may exist in network restoration: where there is a link cut, multiple restoration requests can be initialized, trying to reserve the same wavelength channel on the same link [15-22].

Recent research has shown that outdated link-state information significantly degrades network blocking performance in distributed lightpath provisioning, especially where under traffic with a short average duration of connections [13, 14]. Various solutions have been proposed in the literature to reduce such negative effects [23-31]. A survey of these existing results can be found in Chapter 2.

Chapter 1

We are motivated to conduct in-depth studies on the impacts of outdated link-state information on network performance as well as proposing solutions for reducing such impacts.

1.3 Contributions of the Thesis

The major contributions of the thesis can be summarized as below:

1. We propose a set of general yet accurate analytical models for analyzing different cases with multiple parallel reservation operations along one or multiple different routes between each pair of source-destination nodes. We show that such parallel operations help to greatly reduce the blocking probability caused by outdated link-state information, especially when under light, short-duration traffic loads. Analytical and simulation results reveal the tradeoffs between the control complexity of such parallel-operation schemes and network blocking performance. Extensive simulations also clearly demonstrate the satisfactory accuracy of the proposed models. To the best of our knowledge, this is the first comprehensive study on the benefits of distributed parallel reservation schemes in wavelength-routed networks.
2. We study the case in WDM networks where there are low-frequency global link-state information flooding *and* upon-request local information exchanges. Arguably such a combination provides a more realistic basis for distributed control scheme design since (i) frequent global information flooding can be prohibitively costly in networks with a large number of short-duration connection requests, while (ii) strict local information exchanges cannot easily support dynamic routing decision making. Extensive simulation results show

Introduction

that the proposed schemes indeed steadily outperform the existing schemes with only global flooding or only local information exchanges. More significantly, the impacts of various factors on the proposed schemes, including routing and wavelength assignment algorithm, network topology, number of wavelengths per fiber, global flooding interval and traffic load etc., have been carefully evaluated. Such evaluations help to achieve some insights useful for the future developments of more efficient lightpath provisioning schemes.

3. A new framework of distributed wavelength assignment schemes is proposed, for lowering the blocking probability caused by outdated link-state information in the difficult case of lightpath restoration. Specifically, two simple wavelength assignment methods are developed within the proposed framework. Theoretical analysis shows that both of them achieve the best performance for a special case; while for a few very important more general cases, the optimal performance cannot be guaranteed by *any* distributed wavelength assignment method with a pre-defined wavelength searching sequence. Extensive simulation results demonstrate that the proposed methods significantly outperform the existing ones. The comparisons between the two methods also reveal some interesting insights for efficient restoration scheme design in different networks adopting different routing and wavelength assignment methods in the original lightpath provisioning.

1.4 Thesis Outline

The rest part of this thesis is organized as follows.

Chapter 1

Chapter 2 presents a brief survey of distributed lightpath provisioning in wavelength-routed optical networks, with a main focus on the major challenges and existing solutions we have.

In Chapter 3, a general framework of a large class of distributed lightpath establishment schemes is proposed. Theoretical and simulation studies demonstrate the efficiency of such schemes and the interesting tradeoff between control complexity and network blocking performance. Extensive simulation results also confirm the satisfactory accuracy of the proposed analytical models.

Chapter 4 examines the benefits of combining low-frequency global information flooding and upon-request local link-state information exchanges. Effects of various factors on the proposed solutions are also carefully evaluated. Since it is highly difficult to develop accurate analytical models for dynamic routing schemes, the evaluations are conducted by extensive numerical simulations.

Distributed wavelength assignment in network restoration is studied in Chapter 5, where a novel framework is proposed. Two different wavelength assignment methods are developed within the proposed framework and carefully evaluated and compared with each other. It is confirmed that both of them achieve the best performance for a special case while for a few important more general cases, no method within the same framework can possibly guarantee the optimality. Numerical studies show the different performances of the two methods in different networks adopting different lightpath provisioning schemes at the first place.

Finally, Chapter 6 concludes the thesis and proposes some possible future research directions.

2 Literature Survey

2.1 Lightpath Establishment Problem

In order to implement wavelength-routed WDM networks, there have to be an efficient control scheme for setting up lightpaths upon requests. The problem of finding for a connection request a proper route and assigning a wavelength along the route is known as the *Routing and Wavelength Assignment* (RWA) problem [32]. Typically, traffic patterns may be highly *static* or more *dynamic*. And for these two different cases, the corresponding lightpath establishment problems can be described as follows.

- Under static traffic loads, all the connection requests are known in advance, and the problem is then to set up lightpaths for those connections in a global fashion while minimizing the requested network resources such as the number of wavelengths in the network. Alternatively, the problem can be maximizing the number of requested connections that can be established in a given network. The RWA problem for static traffic is known as the *Static Lightpath Establishment* (SLE) problem [1]. The SLE problem normally can be formulated into an *Integer Linear Program* (ILP) problem [32], which is NP-complete [1]. The ILP

Chapter 2

problems can be solved to achieve optimal solutions for small networks. For large networks, however, heuristics methods usually have to be adopted.

- In the dynamic traffic cases, traffic loads are not known in advance and lightpaths have to be set up adaptively upon the arrivals of connection requests. The routing and the wavelength assignment of each lightpath thus have to be decided adaptively. For such cases, generally the objective of the routing and wavelength assignment schemes is to minimize the connection blocking probability or to achieve best network resource utilizations. The RWA problem in such case is referred to as the *Dynamic Lightpath Establishment* (DLE) problem [33]. The routing and wavelength assignment schemes for the DLE problem generally speaking have to be simple enough to be executed online, yet still capable of efficiently utilizing the network resources to achieve the design objectives.

The DLE problem can be viewed as further including two sub-problems: routing problem and wavelength assignment problem. Each sub-problem can be tackled by adopting some existing heuristics methods. The two sub-problems can be solved jointly or separately.

For the routing sub-problem, three most popular approaches include

- *Fixed routing* method. In this approach, a fixed route is predetermined between each source-destination node pair. An example is the fixed shortest-path routing, in which the route with the minimum number of hops or with the shortest physical length between each pair of source-destination nodes is used. This approach is very simple, and quite effectively in some cases. The main drawback, however, is that it can lead to a high blocking probability when resources along some routes are tied up (though there may be lot of idle capacities elsewhere).

Literature Survey

- *Fixed-alternate routing* method. This routing approach considers multiple different routes between each pair of source-destination nodes [34, 35]. These routes, for example, may include the shortest-path route, the second shortest-path route, the third shortest-path route, etc. To make it work, an ordered list of a number of predefined routes for each source-destination node pair is included in a routing table saved on each node. When a connection request arrives, the source node would attempt these pre-defined routes to see if the request could be accomplished. The intention of using the fixed-alternate routing approaches is to lower the blocking probability caused by a few congested links yet still keep the control complexity at a reasonable, pre-determined level.

- *Adaptive routing*. In this approach, the route from a source node to a destination node is decided adaptively, depending on the network state. A popular adaptive routing method is the *least-congested-path* (LCP) routing [36] method, in which the routes with the least congestion level (The congestion level of a route is typically defined as the traffic load on the most loaded link along this route.) is chosen. To lower the computational complexity, LCP routing could allow a sequence of candidate routes to be pre-selected between each pair of source-destination nodes. Another popular method is the *adaptive shortest-path routing* method for finding the shortest *feasible* path, which may be different from time to time depending on the availability of network resources, between the source-destination nodes [23, 37-40]. Note that by assigning different links with different weights in different manners, the adaptive shortest path algorithm allows sufficient control flexibility. For example, to give a high priority to some connections in using a certain link, we could assign a high weight to this link for the other connections to discourage them from using it. The adaptive routing

Chapter 2

methods overall speaking have the best flexibility and usually the best performance as well. The main drawback is that they also have quite high control complexities.

For the wavelength assignment sub-problem, several most popular heuristics include [41]

- *Random* wavelength assignment method, in which an available wavelength is randomly selected for setting up the lightpath.
- *First-Fit* wavelength assignment, in which all the wavelengths are indexed in a certain way, and among all the available wavelengths, the smallest-indexed one is selected.
- Least Used/SPREAD method [41], which attempts to select the wavelength that is least used in the network. To utilize this method, the link-state information of every link in the network has to be available which sometimes imposes serious additional control overhead. In comparison, the random and the first-fit wavelength assignment methods, if utilized in combination with the fixed routing or fixed alternate-routing method, need only the link-state information of those links along the specific route(s),
- Most Used/PACK method [42]. Unlike the Least Used scheme, this scheme attempts to select the wavelength that is most used in the network. It outperforms the Least Used method significantly [42]. But it also needs the global link-state information of all the links.

To handle the DLE in wavelength-routed WDM networks, the network control may be either centralized or distributed. Under centralized control, a central controller

Literature Survey

is responsible for making RWA decisions for every connection request. Also, it is responsible for sending controlling messages to all the related nodes to make sure that the lightpaths are successfully set up and/or torn down. With the global link-state information being available to a single controller and a single controller making all the decisions, centralized control generally leads to efficient utilizations of network resources in small- or medium-sized networks with highly static traffic loads. In large networks or networks with highly dynamic traffic loads, however, the procedures of collecting the global link-state information, making all the decisions and sending all the control messages becomes a heavy or even unacceptable burden. To deal with the rapid growth of optical networks, especially the rapid growth of optical Internet, distributed control is becoming increasingly important and is being standardized within the framework of *generalized multiple protocol label switching* (GMPLS) [43].

Unlike the centralized DLE, distributed DLE allows the decision-making intelligence to be distributed among the network elements (e.g. the switches/routers). Each individual node in the network can make its own decisions based on the information it has. To facilitate the decision-making, there could be certain kinds of information exchanges between different network nodes. By distributing the burden of decision making to each individual node of the network, distributed control eliminates the heavy burden to the single central controller and is easier to be deployed in large networks. It is also of much better scalability because the control complexity will not increase drastically with the network size.

In this thesis, we focus our discussions on the distributed DLE.

Chapter 2

2.2 Distributed DLE

In distributed DLE, routing and wavelength assignment decisions are made upon the arrivals of connection requests. The control schemes for the distributed DLE can be largely categorized into two different classes:

- Those based on *global* information. In other words, the link-state information is broadcast to all the network nodes or multicast to all the related nodes so that each node always has sufficient information to make its RWA decisions. The well-known schemes belonging to this class include the link-state routing protocol [6], which lets the link-state information be flooded to the whole network and maintains a complete database on every node the status information of every link. Compared to the centralized schemes, this method actually does not reduce information exchange. Only that this time every node could make its own decisions right away without waiting for the central controller's commands. With complete link-state information being available to every node, this method could lead to rather good performance under highly static traffic loads. Under highly dynamic, short-duration traffic loads, however, this method can either lead to unacceptable traffic overhead of link-state information flooding, or it may suffer a very high blocking probability caused by outdated link-state information. Another well-known scheme belonging to this class is the distance-vector method [7]. Unlike the link-state method, it does not maintain on every node a complete database of link-state information, instead it maintains on every node a routing table for each wavelength that specifies the next hop and the distance to each destination on that wavelength. The approach relies on the distributed Bellman-Ford algorithm [8] to maintain

Literature Survey

the routing tables. It requires each node to send routing updates to their neighbors periodically or whenever the status of the node's outgoing links changes so that the routing table on the related nodes could be updated accordingly. While the control traffic overhead for exchanging link-state information is lowered compared to that in the link-state routing scheme, it usually takes a longer interval to update the link-state information and could sometimes cause serious problems such as the routing loop [9]. In addition, the blocking probability caused by outdated link-state information can be still quite high under highly dynamic, short-duration traffic loads.

- Those based on *local* information. In other words, there is no global link-state information flooding or periodical exchange to make sure that the global link-state information is available to every node. In fact, each node even may not maintain a database of link-state information at all. Link-state information exchanges are quite limited and happen only when necessary. This class of schemes could significantly reduce the control traffic overhead and therefore enjoy much better scalability. It arguably may provide a more practical solution for supporting highly dynamic, short-duration traffic loads in large WDM networks. In our project, the main research interests focus on the distributed DLE schemes based on local information.

Most of the local information-based distributed DLE schemes could be viewed as extensions of the two simplest and most basic methods, namely the *source-initiated reservation* (SIR) method and *destination-initiated reservation* (DIR) method [10] respectively. These two methods also provide excellent examples showing the main

Chapter 2

sources of traffic blocking when distributed DLE schemes are adopted. Therefore, we discuss them in more details.

- Source-initiated reservation (SIR). The basic idea is that when a connection request is propagating from the source to the destination, it reserves some capacity along the route. Finally, when the connection request reaches the destination, the destination node will select a wavelength which has been reserved on every hop along the route (if such is available) and send a confirmation request back to the source to confirm the reservation and release the other reserved capacities (if any). If there is not such an available wavelength, the connection request will be blocked. In the SIR scheme, a connection request could reserve all the available wavelengths on every hop along the route (called as the greedy reservation scheme), or it can selectively reserve some of the available wavelengths. The intermediate nodes, if equipped with proper intelligence capabilities, can also release some reserved wavelengths (say, those which are not available in the next hop) even before the connection request reaches the destination node [13]. By using the greedy reservation scheme, the chance that a feasible wavelength is found for this specific connection request is maximized. However, by reserving all the available capacity along the path, it increases the chance that some other connection requests have to be blocked due to the lack of idle capacity. Such is known as the blocking caused by *over-reservation* [13]. By using more intelligent methods, the waste of the capacity could be reduced yet there is the risk that this specific connection request is blocked even though there are actually idle wavelengths along the route (since they are not selected to be reserved).

Literature Survey

- Destination-initiated reservation (DIR). The basic idea is that when a connection request is sent from the source to the destination, it does not reserve any capacity. Instead, it only collects the wavelength usage information along the route. When it reaches the destination node, based on the information it carries, the destination node would choose an appropriate wavelength for the connection request (if such is available), and send a reservation request back to the source node to reserve the selected wavelength along the route. By doing so, the over-reservation problem no longer exists. It has been shown that the DIR method generally outperforms SIR method [10]. However, DIR method also has its own drawbacks. The most significant one is that, due to the propagation delay along the link and the processing delay on each node, the link-state information collected by the connection request could become outdated. In other words, when a reservation request reaches a link intending to reserve a certain selected wavelength channel, it may find that the wavelength channel that was available when the connection request arrived has in the meantime been reserved by another reservation request arrived earlier. Such kind of blocking is called the blocking due to *outdated information* [13]. It has been shown that under highly dynamic, short-duration traffic loads, outdated information becomes the main reason of traffic blocking [13]. In the extreme cases such as that in the WROBS networks [5] where the average duration of each connection is only several dozens or several hundred milliseconds, under light traffic loads virtually all the connection blockings happen in the *backward direction* (i.e., the direction from the destination to the source) [14, 23, 44], caused by outdated information.

Chapter 2

2.3 Outdated Link-State Information: Effects and Control

In the distributed DLE schemes, whether we are using information flooding/exchanges or upon-request information collections, the major challenge remains the same: the network nodes cannot be guaranteed to have the “current” link-state information. In other words, network nodes may have outdated link-state information, either because link-state information is exchanged only periodically, or due to the limit of the network elements’ speed and the unavoidable propagation delay along the links. In small- or medium-sized networks with highly static traffic loads, this is not a big problem. In large networks or networks with highly dynamic traffic loads, this challenge may become very significant.

2.3.1 Effects of the Outdated Link-State Information

Recent research has shown that the outdated link-state information significantly affects the blocking performance in wavelength-routed WDM networks. In [13, 14], by using the DIR method as a case study, it has been shown that blocking due to outdated information dominates network performance under light, short-duration traffic loads. In [11, 12], it is shown that in wavelength-routed networks with periodical or triggered link-state information flooding, the effects of the outdated information remain to be dominant under light traffic loads. Such observations have been repeatedly verified by analytical and simulation results.

2.3.2 Solutions

Various schemes have been proposed to reduce the impacts of outdated link-state information on network blocking performance.

Literature Survey

In [45], the authors propose a novel flooding link-state update method. By actively regulating the link-state update rate and assigning different types of updates with different priorities (such that the outdated link-state information with more significant impacts has a higher chance to be avoided), the proposed method efficiently handles the inherent burstiness of link-state changes and significantly outperform the existing methods when subject to a limited control bandwidth. In [23, 24], the authors propose to activate re-routing operations when there is a blocking due to outdated information.

In [25], a scheme called *intermediate-node initiated reservation* (IIR) is proposed for networks with sparse wavelength conversion. The main idea is to initialize the reservation operations on those nodes with wavelength conversion, before the connection request reaches the destination node, so that the chance of having outdated information is lowered.

Schemes have also been proposed to deploy *parallel* capacity-searching and/or reservation operations, to increase the chance that at least one of them is successful despite of the existence of outdated information. Specifically, in [26, 27], Shami *et al.* proposed to send out multiple connection requests (i.e., parallel capacity searching) but only a single reservation request for setting up a connection. Similar schemes have also been adopted in Quality-of-Service (QoS) routing in packet-switched networks [28] and restoration in WDM networks [29]. Though they increase the chance that at least one connection request could successfully reach the destination node, having parallel capacity searching operations alone cannot significantly weaken the dominant effects of outdated information on the reservation requests under highly dynamic, short-duration connection requests.

Chapter 2

Having parallel capacity reservation operations, on the other hand, helps to achieve much better performance, as later we will see in Chapter 3.

Existing results on parallel reservations in wavelength-routed networks are still quite limited. In [30], the IIR scheme in [25] is extended to allow parallel reservations of multiple wavelengths on the same route. We extend such results to a much more general framework with comprehensive studies. A detailed report is presented in Chapter 3 of this thesis.

Other existing results include the revised flooding scheme for lowering control overhead [46] and research on wavelength assignment methods [19, 20, 47], etc. A careful survey on the latter part will be presented in Chapter 5.

2.4 Control Plane

In the WDM optical networks, network nodes use a control plane to exchange information of network topology and the state of network resources, as well as to establish or tear down lightpaths [48]. Normally the control plane should support several main functions [49] including neighbor discovery, routing, signaling and local resource management, etc. To fulfill these functions, many control protocols have been proposed in the past years. Three major standards development organizations including the *Internet Engineering Task Force* (IETF), the *International Telecommunication Union-Telecommunication Standardization Sector* (ITU-T), and the *Optical Internetworking Forum* (OIF), are focusing on standardizing such control protocols.

Literature Survey

2. 4. 1 Routing Protocol

The functions of a routing protocol include mainly two parts. First, the network topology and resource information are advertised to the whole network or exchanged between some neighborhood nodes. Second, a route is determined based on the available link-state information upon the arrival of a connection request.

In a GMPLS-based optical network, explicit route computations can be realized with the aid of routing protocols and constraint-based routing algorithms. *Open Shortest Path First with Traffic Engineering* (OSPF-TE) is one of the routing protocols with which the routing information including the network topology and resource availability can be exchanged between network nodes.

2. 4. 2 Signaling Protocol

The signaling protocols are responsible for establishing the lightpath after the route is determined as well as tearing it down when data communications are finished. They are also used to exchange control information and reserve network resources. There are two primary types of resource reservation methods: parallel and hop-by-hop reservations. The parallel reservation method reserve network resources on all the links along the route in a parallel manner. By doing so, it can shorten the lightpath establishment delay yet it generally requires rather complete a prior knowledge of link state along the route. By using the hop-by-hop method, on the other hand, the reservation operations are carried out one hop after another. Thus global information may not always be needed.

IETF is standardizing a set of distributed signaling protocols within the GMPLS framework such as the extensions of RSVP-TE [50] and CR-LDP [51]

Chapter 2

Note that both the SIR and the DIR methods can be supported within the GMPLS framework, say, by CR-LDP and RSVP-TE signaling schemes [52, 53] respectively. The open problems include how to implement them with control complexities as low as possible.

2.5 Hardware Implementations

To implement more efficient and cost-effective wavelength-routed networks, several key technologies have been extensively studied in the past few years. Since hardware technologies are not the main focus of this thesis, we provide only a very brief review to the existing results below.

2.5.1 OXC Technologies

The major tasks of a signaling protocol include reserving wavelengths on the links and configuring/reconfiguring OXCs on the nodes for setting up lightpaths. Since optical networks are normally handling high-bandwidth connection requests, the switching time of an OXC becomes an important parameter: a too long switching time means a nontrivial waste of the huge transmission capacity. The switching time of an OXC can vary by several orders of magnitude from nanoseconds to milliseconds, depending on the technologies it adopts and the size of the switch. For example, in an OXC using the popular and mature Micro-Electro-Mechanical Systems (MEMS) technology, tens of milliseconds switching time is usually needed [54], while another OXC solution adopting hologram technology is reported to achieve a switching time of nanoseconds [55]. In an optical mesh network with distributed control management, an OXC may receive many switching requests at the same time. However, not all OXCs are able to

Fig. 2. 1: A logical architecture of an OXC.

handle multiple switching requests simultaneously. A logical architecture of an OXC is illustrated in Fig. 2.1. Based on today's technology there are mainly three different cases [56]:

1. *Sequential cross-connect* (Sequential OXC), where the requested switching operations have to be carried out sequentially. In such case, some switching requests may have to wait in the queue for quite long time, especially when under extensive highly dynamic, short-duration connection requests;
2. *Parallel cross-connect* (Parallel OXC), where each switching request is processed to implement the physical switching operations immediately, without any waiting;
3. *Batch cross-connect* (Batch OXC), where a number of switching requests are batched together to be processed simultaneously, but the next batch of requests have to wait until the current batch requests have been realized.

Chapter 2

Detailed discussions on the current status of OXC technologies can be found in [57-61].

2.5.2 Wavelength Conversion

Wavelength conversion is another key technology for the next-generation wavelength-routed networks. The wavelength-continuity constraint requires that the same wavelength be assigned on all the links along a route. Wavelength conversion can relax or even eliminate this constraint, and thus helps to significantly lower network blocking probability. Currently wavelength conversion is still an expensive and immature technology.

Wavelength conversion techniques can be generally classified into two types:

Fig. 2. 2: An example of an optoelectronic wavelength converter.

Fig. 2. 3: An example of an all-optical wavelength converter.

1. *Optoelectronic wavelength conversion*, where the input signal is firstly converted to electronic form, regenerated, and then retransmitted using a laser at a different wavelength. An example of optoelectronic wavelength conversion is illustrated in Fig. 2.2. It is an expensive solution due to the extensive optic-electro-optic (O/E/O) conversions.

2. *All-optical wavelength conversion*, where the input signal is converted in optical domain by using optical gating or four-wave-mixing effects. The leading implementation is the *semiconductor optical amplifier* (SOA) wavelength converter. A simple example is provided in Fig. 2.3. In such wavelength conversion, the control signal could be either electronic or optical.

Detailed discussions on the current status of wavelength conversion technologies can be found in [62- 67].

Chapter 2

2.6 Summary

In this chapter, to provide a general background for the later discussions on the effects of outdated link-state information in distributed DLE and the control of such effects, we proposed a brief survey of the existing studies on lightpath establishment problem, especially the distributed DLE problem. Main implementation issues including the control and signaling protocols and the hardware constraints have also been briefly discussed. In the following chapters, studies will be conducted with the main objective of achieving more in-depth understandings of such effects as well as proposing some effective solutions.

3 Evaluation and Analysis of Distributed Parallel Reservations

3.1 Introduction

As described in Chapter 2, a major challenge in distributed lightpath provisioning is that unavoidably network nodes may have outdated link-state information, either because link-state information is exchanged only periodically, or due to the propagation delay along the links. In [13, 14], the authors demonstrate that blocking due to outdated information dominates the network performance under light, short-duration traffic loads. Specifically, when a reservation request reaches a link intended to reserve a certain wavelength, it may find that the wavelength that was available when the connection request arrived has in the meantime been reserved by another, earlier arrived, reservation request.

Many schemes have been proposed to reduce the impact of outdated link-state information. Some of them have been proposed to deploy parallel capacity-searching and/or reservation operations, to increase the chance that at least one of them is successful despite of the existence of outdated information. A detailed survey is provided in Chapter 2.

We propose in [31] a general framework termed *Multi-Path Parallel Reservation* (MPPR). Specifically, to set up a lightpath, the source node can either send out a

Chapter 3

single connection request, as in the classic DIR method, or multiple connection requests along multiple different routes simultaneously. The destination node, upon receiving the connection requests, can respond to some or all of them, reserving on each route one or multiple wavelengths. Fig. 3.1 illustrates a special case of MPPR where there is one reservation on each of the two candidate routes. Preliminary results in [31] show that a correct number of parallel reservations significantly lowers network blocking under light, highly dynamic traffic. Too many parallel reservations, on the other hand, lead to high control overhead and may actually increase network blocking by over-reserving network capacities.

Parallel capacity-search and reservation operations are not only effective in helping lower the blocking probability of distributed DLE, they may also contribute to enhance the next-generation optical Internet. For example, in optical Internet with combined advance reservation and immediate reservation [68], parallel capacity-search operations allow each immediate reservation to choose from several candidate routes the best one. In networks with impairment-awareness request [69], parallel search and reservation enables the comparisons of signal quality along several different routes such that the qualified one(s) can be selected.

In this chapter, we focus on studying DLE methods with parallel reservation operations. By using the MPPR method as a case study, we evaluate the performance of parallel reservations in distributed wavelength-routed networks. We develop general but accurate analytical models and conduct extensive simulations as well. Analytical and simulation results provide insightful understandings of the performance of different parallel reservation schemes under different traffic loads in

Evaluation and Analysis of Distributed Parallel Reservations

different networks. Discussions on the different schemes' control overhead are also provided.

The rest part of this chapter is organized as follows. In Section 3.2, we present the general framework of MPPR and then describe several specific schemes which we would evaluate in detail later. Analytical models are proposed in Section 3.3 following a brief survey of the related existing results. Section 3.4 presents numerical results and discussions. Section 3.5 concludes the chapter.

3.2 Multi-Path Parallel Reservation Schemes

We choose the rather general multi-path parallel reservation (MPPR) method as a case study, such that the main idea for developing the analytical models as well as most observations would remain valid for many other parallel reservation schemes.

3.2.1 Framework of the Multi-Path Parallel Reservation Method

The framework of the MPPR method can be described as follows. To set up a lightpath, the source node sends out a certain number of connection requests along a set of alternative routes, one request on each route. Upon the arrival of a connection request, the destination node could either simply drop it, or send a reservation request back to the source node, reserving one or multiple wavelengths along this route.

Once the first successful reservation request reaches the source node, data transmission starts immediately on one of the reserved wavelengths, while the other reserved wavelengths on the same route (if any) are released. Later when the other reservation requests (if any) arrive, immediate release requests will be initialized in response.

Chapter 3

Fig. 3. 1: An example of MPPR scheme where we have two candidate routes and one reservation on each route (i.e., the 2P-2R scheme).

Evaluation and Analysis of Distributed Parallel Reservations

3. 2. 2 Several Specific MPPR Schemes

In MPPR, a good balance needs to be kept between network performance and control overhead. As mentioned earlier, too many parallel reservations lead to a high control overhead, and may actually degrade network blocking performance. To keep control overhead at an acceptable level, we consider only those MPPR schemes subjecting to the following conditions:

- To establish a lightpath, there could be at most two connection requests on two link-disjoint alternative routes.
- On each route, a reservation request can reserve at most two wavelengths.

The first constraint also helps reduce the average length of each lightpath, since the third link-disjoint route between a pair of nodes, if exists at all, is typically quite long in a sparse network. The second constraint is adopted because of the following reasons: 1) having more reservations per route may lead to significant over-reservations, which degrades the network performance under heavy traffic loads; 2) under medium and light traffic loads, reserving two wavelengths can sufficiently reduce the blocking caused by outdated information as later we will see, thus reserving more wavelengths is not necessary.

Specifically, we discuss several schemes as follows:

- *Single-path single-reservation* (1P-1R) method, i.e., the classic DIR method.

This classic method provides a benchmark for our performance evaluations.

- *Single-path double-reservation* (1P-2R) method is nearly the same as the 1P-1R method except that each reservation request can reserve two wavelengths

Chapter 3

(if such are available) along the route. If both wavelengths are successfully reserved, one of them will be randomly selected for data transmission while the other one would be released immediately.

- *Alternate-path single-reservation (2P-1R)* method, where there are two connection requests on two link-disjoint routes, yet only a single reservation request in response to the first successful connection request, reserving one wavelength along its route. This method is the same as the method proposed in [27].
- *Alternate-path double-reservation (2P-2R)* method, which sends out two connection requests on two alternative routes, and one reservation request in response to each successful connection request, reserving one wavelength on each route. The example in Fig. 3.1 illustrates the 2P-2R method.
- *Alternate-path four-reservation (2P-4R)* method is similar to the 2P-2R method, except that each reservation request reserves two wavelengths (if applicable) along its route. Therefore the source node needs to release a maximum of three reserved wavelengths.

3.3 An Analytical Model

Blocking probability has traditionally been used as a key metric for measuring the performance of wavelength-routed networks. Various models have been developed for analyzing the network blocking performance. In this section, following a brief survey of the existing results, we propose our new models. To the best of our knowledge, this is the first time distributed *parallel* reservation schemes are analyzed.

Evaluation and Analysis of Distributed Parallel Reservations

The model is applicable to virtually all schemes within the MPPR framework, while its main idea applies to analyzing many other distributed parallel reservation schemes.

3.3.1 Previous Work

Extensive research has been conducted on analyzing centralized-controlled lightpath provisioning. Existing results generally aim to achieve higher accuracy (e.g., by carefully measuring the effects of traffic correlations [70-73]), or to simplify analytical model without significantly sacrificing accuracy (e.g., [74]). The most significant contributions include (i) the adoption of the reduced load approximation approach [75] with the state-dependent arrival model [76] in blocking analysis [70]; and (ii) the evolution from link-independent to link-correlation model [71] (which later was greatly simplified in [74]), etc. A comprehensive survey of the existing results can be found in [13]. While most of the previous work has been done for fixed routing schemes, alternative-path routing schemes [34, 35, 74], dynamic routing schemes [77, 78], and the more general case under heterogeneous traffic [79] have also been analyzed.

The first analytical model for distributed lightpath provisioning is proposed in [14], where the effect of outdated link-state information is taken into consideration. However, by adopting the link independent assumption, the analytical model is rather simple but not very accurate. The analysis accuracy is later improved in [13], where link correlation and effects of propagation delay are taken into account. Both of these results consider the classic DIR method where a single reservation request is initialized for establishing a lightpath. In the next subsection, we extend them to analyzing parallel reservation schemes requiring nontrivial modifications.

Chapter 3

3.3.2 Analytical Models of Parallel Reservation Schemes

Compared to the analysis of the classic DIR method, blocking analysis of parallel reservation schemes requests nontrivial extensions, mainly because of the strong correlations between the parallel reservation operations. Specifically,

- For the cases where *not every* connection request initializes a reservation request, whether to initialize a reservation request or not generally depends on the status of the other reservation requests between the same source-destination nodes. Such strong correlations greatly complicate the blocking analysis.
- When multiple wavelengths are reserved for setting up a lightpath, either on a single route or on multiple candidate routes, their respective durations are strongly correlated. In fact, all but one of them will be released shortly. These temporary reservations, however, still consume some network capacities. Under traffic with short durations of connections, such kind of capacity consumptions may significantly affect the network performance and therefore cannot be neglected.
- For the cases where there are multiple parallel reservations for setting up a connection between each pair of source-destination nodes, arrivals of reservation requests are not Poisson-distributed. Such kind of non-Poisson distributions are difficult to analyze, especially when the multiple reservations are on a same route leading to even stronger correlations

We start by considering the relatively simple cases where each successful connection request initializes a *single* reservation request reserving a *single*

Evaluation and Analysis of Distributed Parallel Reservations

wavelength on its route. We see that among the specific schemes listed in Section 3.2.2, 1P-1R and 2P-2R methods belong to this category. Discussions on such cases form a basis for further extensions to analyzing the otherwise cases, as later we will see.

To address these problems, we introduce the concept of *attempting connection*. Specifically, we define each $nP-nR$ ($n \geq 1$) reservation operation as composed of n attempting connections, each of which containing a single connection request and a single reservation request attempting to set up a single lightpath, just as that in the classic DIR method. For example, a 2P-2R operation could be viewed as composed of two attempting connections. By doing so, the case with only one of two connection requests reaching the destination could be viewed as having one attempting connection blocked in the *forward direction* (i.e., the direction from the source to the destination); while the case with only one of two reservation requests successfully reaching the source could be viewed as having one attempting connection blocked in the *backward direction* (i.e., the direction from the destination to the source). More significantly, by introducing this definition, a temporary reservation (if any) could be viewed as a successful attempting connection with *zero* data-transmission duration. Therefore, parallel reservation schemes could be viewed as extensions of the classic DIR scheme where *arrivals* and *durations* of attempting connections are strongly correlated. Since fully reflecting all the correlation effects would make blocking analysis prohibitively complicated, to keep a balance between complexity and accuracy, we take some correlation factors into account while making assumptions to simplify the others. Specifically,

Chapter 3

- We approximate the non-Poisson *arrivals* of parallel reservations as a Poisson process. In other words, n parallel reservations between a same pair of source-destination nodes are approximated as n attempting connections arriving from a Poisson process. Though this approximation tends to underestimate the burstiness of reservation operations, it greatly simplifies the analytical model. As later we would see, analytical results remain as highly accurate in both mesh- and ring-topology networks.
- The strong correlations between the *durations* of different attempting connections, on the other hand, are carefully reflected in the model, as later we will present in detail.

Next we discuss the proposed analytical model in detail.

1) Assumptions

We adopt the following assumptions in our analysis:

- The network consists of J links connected in an arbitrary fashion.
- Each link has C wavelengths.
- Between each source-destination node pair S , there are n_s attempting connections, indexed from 1 to n_s in an increasing order of their respective length of routes. To break a tie, the attempting connection leading to lightpath establishment (if any) is assigned the smallest index while the others are assigned randomly. To simplify the analysis, throughout this chapter we assume that successful connection requests on lower-indexed routes always reach the destination node earlier. As long as no confusion

Evaluation and Analysis of Distributed Parallel Reservations

would be caused, we denote the i -th attempting connection between node pair S , $1 \leq i \leq n_s$, as well as its route as $R(i)$. When there is no need to specify the index of an attempting connection, we denote the attempting connection as well as its route as R .

- The duration of each data transmission follows the exponential distribution with an average interval of $1/\mu$.
- There is no wavelength conversion in the networks. Therefore the wavelength-continuity constraint applies.
- The wavelength assigned to each attempting connection is randomly selected from the set of wavelengths that are available along the route.

To simplify the descriptions, we use the same notations as those in [13]. Specifically, we call the blocking in the forward direction the *forward blocking*; and the blocking in the backward direction the *backward blocking*. Between the two end nodes of each link along a route, we call the one closer to the source the *left-hand* node, and the one closer to the destination the *right-hand* node. We let the *link state* be the state of a link when a connection request reaches the right-hand node of the link. We define that a wavelength channel can be in one of the following three states: (1) free; (2) reserved, yet no data transmission; and (3) occupied by data transmission. We shall say that in the state (3), the wavelength channel is *busy*; otherwise, it is *idle*.

2) Framework of the Analytical Model

Following [13], we let X_j ($j=1,2,\dots,J$) be the random variable representing the number of idle wavelength channels on link j . Let

Chapter 3

$$q_j(m) = \Pr\{X_j = m\}, m = 1, 2, \dots, C \quad (3.1)$$

be the probability that there are exactly m idle wavelength channels on link j .

Following [76], we assume that all X_j 's are mutually independent, that is,

$$q(\mathbf{m}) = \prod_{j=1}^J q_j(m_j) \quad (3.2)$$

where

$$\mathbf{m} = (m_1, m_2, \dots, m_J).$$

We further assume that when there are m idle wavelength channels on link j , the inter-arrival time of attempting connections is exponentially distributed with a parameter $\alpha_j(m)$, which is called the *state dependent arrival rate* [76]. Note that, in our analysis, there are some zero-duration attempting connections. We introduce a parameter $\rho_j(m)$, which denotes the probability that an attempting connection passing through link j is of a *non-zero* duration, given that there are m idle wavelengths on the link. It then follows that the number of idle wavelengths on link j can be modeled as the outcome of a birth-death process as shown in Fig. 3.2. Specifically, we have

$$q_j(m) = \prod_{k=1}^m \frac{C-k+1}{\alpha_j(k) \cdot \rho_j(k)} \cdot \mu^m \cdot q_j(0), m = 1, 2, \dots, C \quad (3.3)$$

where

$$q_j(0) = \left[1 + \sum_{m=1}^C \prod_{k=1}^m \frac{C-k+1}{\alpha_j(k) \cdot \rho_j(k)} \cdot \mu^m \right]^{-1}. \quad (3.4)$$

Evaluation and Analysis of Distributed Parallel Reservations

Fig. 3. 2: The birth-death process of different link states in wavelength-routed networks with distributed parallel reservations.

Finally, the framework of the analytical model can be summarized as follows:

◇ Analytical Model: Framework

1) Initialize $\alpha_j(m)$ and $\rho_j(m)$, $j = 1, 2, \dots, J$, as follows:

$$\alpha_j(m) = \begin{cases} \sum_{R: j \in R} \lambda_R, & m = 1, 2, \dots, C, \\ 0, & m = 0. \end{cases} \quad (3.5)$$

$$\rho_j(m) = \begin{cases} 1, & m = 1, 2, \dots, C, \\ 0, & m = 0. \end{cases} \quad (3.6)$$

2) Calculate $q(\mathbf{m})$ through (3.1)-(3.4).

3) Calculate the blocking probability of the attempting connections between node pair S as follows:

$$B_{R(i)} = B_{R(i)}^F + (1 - B_{R(i)}^F) \cdot B_{R(i)}^B, i = 1, 2, 3, \dots, n_S \quad (3.7)$$

Chapter 3

where $B_{R(i)}^F$ and $B_{R(i)}^B$ denote the forward blocking probability and the backward blocking probability of the attempting connection $R(i)$, respectively.

4) Calculate the blocking probability of node pair S as:

$$B_S = \prod_{i=1}^{n_s} B_{R(i)}. \quad (3.8)$$

If for every node pair S, B_S has been convergent, then stop; otherwise, go to step 5).

5) Update $\alpha_j(m)$ and $\rho_j(m)$, $j = 1, 2, \dots, J$, as follows:

$$\begin{aligned} \alpha_j(m) &= \sum_{R: j \in R} \lambda_{R,j}(m) \\ &= \sum_{R: j \in R} \lambda_R \cdot (1 - B_{R|X_j=m}) \end{aligned} \quad (3.9)$$

where $\lambda_{R,j}(m)$ denotes the arrival rate of the successful attempting connections on route R (including those with zero data transmission duration), given that the state of link j is m .

$$\rho_j(m) = \frac{\mu_1}{\sum_{R: j \in R} (1 - B_{R|X_j=m})} \quad (3.10)$$

where

$$\begin{aligned} \mu_1 &= \sum_{R: R \in R_j^{(1)}} (1 - B_{R|X_j=m}) \\ &+ \sum_{i=2}^{n_s} \sum_{R: R \in R_j^{(i)}} \left((1 - B_{R|X_j=m}) \cdot \prod_{l < i} B_{R(l)} \right), \end{aligned}$$

Evaluation and Analysis of Distributed Parallel Reservations

$R_j^{(i)}$, $i \in \{1, 2, \dots, n_s\}$, denotes the set of the i -th attempting connections passing through link j , $B_{R(i)}$ denotes the blocking probability of the attempting connection $R(i)$, and $B_{R|X_j=m}$ denotes the conditional blocking probability of the attempting connection on route R given that the state of link j is m . The calculations of $B_{R|X_j=m}$ remain the same as those in [13]. Go to step 2).

Remark: Eq. (3.10) reflects the correlations between two different parts of successful attempting connections: those finally leading to lightpath establishments, and those temporary ones.

We next discuss the calculations of $B_{R(i)}^F$ and $B_{R(i)}^B$, respectively.

3) Calculations of $B_{R(i)}^F$ and $B_{R(i)}^B$

The calculations of $B_{R(i)}^F$ and $B_{R(i)}^B$ could be viewed as extensions of the models proposed in [13]. Specifically, let $h_{n,R(i)}$ denote the probability that a given set of n wavelength channels are free on route $R(i)$ at the moment when the connection request reaches the destination node. Since there is only a single reservation on each route, calculations equations proposed in [13] can be adopted without any change. Specifically,

$$B_{R(i)}^F = 1 - \sum_{n=1}^C (-1)^{n+1} \binom{C}{n} h_{n,R(i)}, \quad (3.11)$$

where

Chapter 3

$$h_{n,R(i)} = \begin{cases} h_{n,1}, & \text{if } L_{R(i)} = 1, \\ h_{n,1} \cdot \prod_{j=2}^{L_{R(i)}} h_{n,j|n,j'}(t_j), & \text{otherwise.} \end{cases} \quad (3.12)$$

In this equation, $L_{R(i)}$ denotes the hop length of route $R(i)$; link j and j' denotes the j -th and $(j-1)$ -th (where $L_{R(i)} > 1$) link of route $R(i)$, respectively; and $h_{n,j|n,j'}(t_j)$ denotes the conditional probability that a given set of n wavelengths are free on link j , given that t_j time slots ago they were free on link j' , where t_j denotes the propagation delay on link j .

For the backward blocking, if $L_{R(i)} = 1$, obviously $B_{R(i)}^B = 0$. When $L_{R(i)} > 1$, we have

$$B_{R(i)}^B = 1 - \prod_{j=1}^{L_{R(i)}-1} \omega_{j,j''}(t_{R(i)}(j)) \quad (3.13)$$

where j'' denotes the $(j+1)$ -th link of route $R(i)$, and $\omega_{j,j''}(t_{R(i)}(j))$ denotes the conditional probability that no interfering reservation request has arrived link j within the past $t_{R(i)}(j)$ time slots and reserved the same wavelength channel, given that j'' is not on the route of that interfering request. Here $t_{R(i)}(j)$ denotes the round-trip propagation delay between the right-hand node of the link j and destination node of the route $R(i)$.

The calculations of $\omega_{j,j''}(t_{R(i)}(j))$, $h_{n,R(i)}$ and $h_{n,j|n,j'}(t_j)$ can be found in [13].

4) Extensions to the Cases Where There Are Multiple Reservations on Each Route

Evaluation and Analysis of Distributed Parallel Reservations

We now extend the proposed model to analyze the cases where there are $n_{R(i)}$ ($n_{R(i)} > 1$) parallel reservations on a same route $R(i)$. Among the specific schemes listed in Section 3.2.2, 1P-2R and 2P-4R schemes belong to such cases. By viewing $n_{R(i)}$ parallel reservations as $n_{R(i)}$ attempting connections, we refine Eq. (3.11) by adopting Jordan Theorem [80] as follows:

$$B_{R(i)_k}^F = 1 - \sum_{n=k}^C (-1)^{n-k} \cdot \binom{n-1}{n-k} \cdot \binom{C}{n} \cdot h_{n,R(i)}, \quad k=1,2, \dots, n_{R(i)} \quad (3.14)$$

where $R(i)_k$ denotes the k -th attempting connection on route $R(i)$. By doing so, we measure the probability of having fewer than m free wavelengths along the route. Another change is to let

$$B_{R(i)_k | x_j=m}^F = \begin{cases} 1 & \text{if } m < k \\ 1 - \sum_{n=k}^C (-1)^{n-k} \cdot \binom{n-1}{n-k} \cdot \binom{C}{n} \cdot h_{n,R(i) | x_j=m} & \text{otherwise} \end{cases}, \quad (3.15)$$

where $k=1,2, \dots, n_{R(i)}$.

Note that the calculations of backward blocking could also be affected where there are parallel reservations on a same route. Specifically, the wavelength assignment of each reservation operation is not strictly “random” since different reservation operations on a same route have to select different wavelengths. Taking this effect into consideration, however, makes the analytical model rather complicated. Therefore, we neglect this factor in our analysis, which generally leads to slight under-estimations of the backward blocking probability.

Chapter 3

The strong correlations between *forward* blocking of different attempting connections, however, cannot be neglected. Specifically, if the first attempting connection on a route is blocked, all the other attempting connections on the same route will be blocked (since the attempting connection leading to lighpath establishment is assigned the smallest index among all the attempting connections on a same route). In other words, the forward blocking of a route $R(i)$ equals to the forward blocking of the first attempting connection on this route. By assigning smaller indexes to those attempting connections blocked in backward direction followed by those blocked in forward direction, we revise Eq. (3.7) as follows:

$$B_{R(i)} = B_{R(i)_1}^F + \sum_{l=1}^{n_{R(i)}-1} \left\{ \prod_{k=1}^l [(1 - B_{R(i)_k}^F) \cdot B_{R(i)_k}^B] \cdot B_{R(i)_{l+1}}^F \right\} + \prod_{k=1}^{n_{R(i)}} (1 - B_{R(i)_k}^F) \cdot B_{R(i)_k}^B, \\ i = 1, 2, 3, \dots, n_S. \quad (3.16)$$

Finally, Eq. (3.10) also needs to be revised to reflect the fact that a successful attempting connection is of a non-zero data-transmission duration if and only if 1) it is of the smallest index among all the attempting connections on its route; and 2) attempting connections on shorter routes between the same source-destination nodes have all been blocked. We have

$$\rho_j(m) = \frac{\mu_2}{\sum_{R: j \in R} \sum_{n=1}^{n_{R(i)}} [n \cdot B_{R^n | X_j=m-n} \cdot \prod_{k=1}^n (1 - B_{R_k | X_j=m-k+1})]} \quad (3.17)$$

where

$$\mu_2 = \sum_{R: R=R_{(i)}^{(1)}} (1 - B_{R | X_j=m}) + \sum_{i=2}^{n_R} \sum_{R: R=R_{(i)}^{(1)}} ((1 - B_{R | X_j=m}) \cdot \prod_{l < i} B_{R(l)}),$$

Evaluation and Analysis of Distributed Parallel Reservations

n_R denotes the number of candidate routes between the same source-destination nodes, $R = R_{(i)}^{(1)}$ denotes that R is of the smallest index among all the successful attempting connections on route $R(i)$, and $B_{R^n|X_j=m-n}$ denotes the probability of having exactly n ($1 \leq n \leq n_{R(i)}$) successful attempting connections on route $R(i)$,

$$B_{R^n|X_j=m-n} = B_{R(i)_{n+1}|X_j=m-n}^F + \sum_{l=n+1}^{n_{R(i)}-1} \left\{ \prod_{k=n+1}^l \varphi(k) \cdot B_{R(i)_{l+1}|X_j=m-n}^F \right\} + \prod_{k=n+1}^{n_{R(i)}} \varphi(k), \quad (3.18)$$

where

$$\varphi(k) = (1 - B_{R(i)_k|X_j=m-n}^F) \cdot B_{R(i)_k|X_j=m-n}^B.$$

5) Extensions to the Cases Where Not Every Successful Connection Request Initializes a Reservation

The proposed analytical model can also be extended to analyze those schemes where *not every* successful connection request initializes a reservation request, e.g., 2P-1R. We call such kind of parallel reservations schemes as *non-aggressive reservation* schemes. To develop a single general model for analyzing all the different non-aggressive reservation schemes may not be feasible, especially for the case where different connection requests are allowed to trigger different numbers (including zero) of reservation requests. Therefore, we restrict ourselves to discuss the important special case where reservations requests are triggered in response to the *earliest* successful connection requests, until either a total of n reservation requests have been

Chapter 3

initialized, or every successful connection request has been responded with a reservation.

We first study the scheme with at most *one* reservation request initialized on each route. For such case, an n_R P- n R operation, where $n_R > n \geq 1$, can be viewed as containing n attempting connections. For the i -th ($1 \leq i \leq n$) attempting connection, we have that its forward blocking probability equals to

$$B_{R(i)}^F = \Pr\{N_{SCR} < i\} = \sum_{k=0}^{i-1} \Pr\{N_{SCR} = k\} \quad (3.19)$$

where N_{SCR} denotes the number of successful connection requests. In other words, the i -th attempting connection is blocked in forward direction if and only if there are fewer than i connection requests successfully reaching the destination. The probability $\Pr\{N_{SCR} = k\}$ can be calculated by summing up the blocking probabilities of $\binom{n_R}{k}$ different cases where in each case only a specific set of k connection requests are *not* blocked in forward directions.

To calculate the backward blocking, we see that the i -th attempting connection has a backward blocking on the j -th route ($j \geq i$) if and only if the following three conditions are all satisfied:

- 1) There are $i-1$ successful connection requests on the first $j-1$ routes;
- 2) There is no forward blocking on the j -th route; and
- 3) There is backward blocking on the j -th route.

Evaluation and Analysis of Distributed Parallel Reservations

Calculations of all these three probabilities are straightforward. Denote the first probability as

$$P_1(i, j) = \Pr\{N_{SCR} = i - 1 | N_{route} = j - 1\}$$

where $i \leq j$; the second probability as $(1 - B_j^F)$; and the third probability as B_j^B . The probability that the i -th attempting connection has a backward blocking on the j -th route can be formulated as

$$B_{R(i)|j}^B = \begin{cases} 0, & i > j, \\ P_1\{i, j\} \cdot (1 - B_j^F) \cdot B_j^B, & i \leq j. \end{cases} \quad (3.20)$$

The overall backward blocking of the i -th attempting connection therefore can be formulated as

$$B_{R(i)}^B = \sum_{j=1}^{n_R} B_{R(i)|j}^B. \quad (3.21)$$

The 2P-1R scheme, as a special case with only one attempting connection, can be analyzed by adopting Eqs. (3.19)-(3.21). Specifically, the forward blocking is

$$B^F = B_{R(1)}^F \cdot B_{R(2)}^F. \quad (3.22)$$

And the backward blocking is

$$B^B = (1 - B_{R(1)}^F) \cdot B_{R(1)}^B + B_{R(1)}^F \cdot (1 - B_{R(2)}^F) \cdot B_{R(2)}^B. \quad (3.23)$$

The model can be further extended to handle the cases where there could be multiple reservations on each route. However, the detailed discussions, though not very difficult, are very lengthy. Therefore they are omitted in this chapter.

Chapter 3

Finally, the main contributions of the proposed analytical models can be summarized as follows:

- By introducing the concept of attempting connection, we provide a general framework for analyzing different parallel reservation schemes.
- By treating those temporary connections as successful attempting connections with zero data-transmission duration and formulating the correlations between different attempting connections' durations, as shown in Eqs. (3.10) and (3.17), we propose a general method for analyzing the over-reservation effects in distributed parallel reservations.
- For analyzing the schemes where there are multiple reservations on a same route, we take into account the strong correlations between forward blocking of different attempting connections (Eq. (3.16)), while Jordan Theorem (Eq. (3.14)) is adopted as well.
- Non-aggressive reservation schemes are analyzed by adopting the simple strategy of viewing each mP - nR reservation operation as composing of n attempting connections.

3.4 Numerical Results and Discussions

In this section, blocking performance of several MPPR schemes is evaluated by extensive simulations and analyses, while the accuracy of the proposed analytical models is also verified. The simulations were conducted on PacNet (as shown in Fig. 3.3, where the numbers next to the links denote the physical lengths in tens of kilometers) and a 12-node ring network (where the length of each link is 20 km), respectively. We assume that (1) each link is composed of two directional fibers of

Evaluation and Analysis of Distributed Parallel Reservations

Fig. 3. 3: Topology of PacNet.

opposite directions, with eight wavelengths per fiber unless otherwise specified; (2) lightpath establishment requests are uniformly distributed between each pair of source-destination nodes with exponentially-distributed durations; and (3) random wavelength assignment is adopted by every reservation request. In [13], it is shown that under dynamic traffic with short average durations of connections, random wavelength assignment method outperforms the first-fit wavelength assignment method.

To better resemble the real-world cases, we further assume that (1) control messages are handled in the First-Come-First-Serve (FCFS) manner on each node, where the processing time of each connection/reservation/release request is $10\ \mu\text{s}$; (2) *parallel OXC* [56], which handles multiple switching operations in parallel, is employed on each node, with a switching time of $500\ \mu\text{s}$; and (3) upon receiving a reservation request, a node always forward the request immediately after processing

Chapter 3

without waiting for the configuration of the local OXC, i.e., the *Forward before XC* (FBXC) scheme [56] is adopted.

To study the effects of proposed schemes, we run simulations for different cases with extra short (10 ms), short (100 ms) and long (1000 seconds) average durations of connections, respectively. The traffic loads are measured by the average traffic sourced from each node on each wavelength, ranging from 0.01 to 1 Erlang.

3.4.1 Evaluations of the Blocking Performance

Traffic load affects the network blocking probability in two different aspects: network resource availability and probability of having outdated information. Heavier traffic loads generally speaking make both aspects become worse, leading to higher blocking probability. The more interesting observations, however, come from comparing the performances of different methods under light and heavy traffic loads respectively. Fig. 3.4 plots blocking probabilities vs. traffic loads with a short average duration of connection for different MPPR schemes in different networks. Under light traffic loads, we see that 1P-2R, 2P-2R and 2P-4R significantly outperform 1P-1R and 2P-1R. In other words, by having multiple parallel reservations, either along a same route or several different routes, the dominant backward blocking caused by outdated link-state information can be significantly lowered. Although parallel reservations cause some over-reservations of network capacities, the side effects are outweighed by the improvements.

Under heavy traffic loads, however, the observations are quite different. Specifically, in general mesh-topology networks, blocking performance is largely decided by the number of candidate routes rather than the number of reservations. Having more candidate routes generally leads to better performance. This is because

Evaluation and Analysis of Distributed Parallel Reservations

(a) PacNet

(b) 12-node ring

Fig. 3. 4: Blocking performance of the different parallel reservations schemes under traffic with an average duration of each connection of 100ms.

Chapter 3

that under heavy traffic loads, forward blocking is dominant. Therefore, having multiple candidate routes helps to increase the probability that at least one connection request could successfully reach the destination, whereas the number of reservations cannot significantly affect network performance. This conclusion also holds in ring networks, though the strong correlations reduce the significance of having two candidate routes and finally push the performance of all the schemes to be nearly the same under very high traffic loads.

From the same figure, we see that 2P-2R performs nearly the same as 1P-2R in PacNet under low traffic loads. Then 2P-2R steadily outperforms 1P-2R when overall network blocking probability is higher than 10^{-4} . In other words, within a wide range of traffic loads, having parallel reservations on different routes achieves better performance than having them on a same route. This is because that by having multiple reservations on different routes, we have better load balance of reservation requests in the networks, which helps to avoid overloading some “hotspot” links. Such observation becomes even more obvious in ring networks, where 2P-2R always performs much better. Comparing 2P-2R and 2P-4R, we see that the latter one performs better under low traffic loads, yet slightly outperformed by the former one in the ring network under heavy traffic loads, where over-reservation effects become significant enough. Note that all the above observations apply to the case under traffic loads with an extra short average duration of connection. Only that blocking probabilities become much higher when the average duration of each connection becomes shorter, especially under light traffic loads.

Blocking performance of different schemes under traffic loads with a long average duration of connection is plot in Fig. 3.5. In such cases, since outdated link-

Evaluation and Analysis of Distributed Parallel Reservations

(a) PacNet

(b) 12-node ring

Fig. 3. 5: Blocking performance of different parallel reservations schemes under traffic loads with an average duration of each connection of 1000s.

Chapter 3

state information is no longer a significant factor, network blocking virtually all happens in forward direction, caused by insufficient network capacities. As a result, we see that the performance is decided by the number of candidate routes rather than the number of parallel reservations: the methods with two candidate routes outperform the methods with a single route. That is easy to understand, with more candidate routes, the chance that a feasible solution can be found while subject to network resource constraints would become higher.

The differences of the blocking performance as presented in Fig. 3.4 and Fig. 3.5 comes from the different average duration of each connection. Networks have less outdated link-status information when under traffic load with a longer average duration of connections. The blocking probability therefore becomes lower. The differences between performances under long- and short-duration traffic loads are more significant in a ring network than in a mesh network, since the former one is more sensitive to outdated information.

3. 4. 2 Accuracy of Proposed Analytical Model

Analytical results cannot be perfect accurate. The errors typically come from the simplifications we have to adopt in approximating the highly complicated correlations between different lightpath establishment operations. Without such approximations, blocking performance analysis may become impossible. Figs. 3.6-3.10 evaluate the accuracy of the proposed models in different cases with extra short (10 ms), short (100 ms) and long (1000s) average durations of connections, respectively. For each simulation point, we generate 10^6 connection requests and both the average and 95% confidence interval are given. To make fair comparisons, processing delay and queuing delay on each node is neglected in simulations. We see that though the

Evaluation and Analysis of Distributed Parallel Reservations

(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 3. 6: Accuracy of the analytical models in PacNet under short-duration traffic with an average duration of connection of 100 ms.

Chapter 3

(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 3. 7: Accuracy of the analytical models in 12-node ring under short-duration traffic with an average duration of connection of 100 ms.

Evaluation and Analysis of Distributed Parallel Reservations

(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 3. 8: Accuracy of the analytical models in PacNet under long-duration traffic with an average duration of connection of 1000 s.

Chapter 3

(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 3. 9: Accuracy of the analytical models in 12-node ring under long-duration traffic with an average duration of connection of 1000 s.

Evaluation and Analysis of Distributed Parallel Reservations

(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 3. 10: Accuracy of the analytical models in PacNet under extra short-duration traffic with an average duration of connection of 10 ms.

Chapter 3

proposed analytical models are quite general, the analysis results remain rather accurate for all the five different schemes in PacNet. In ring network where there exist strong correlations between traffic loads, accuracy of the analytical models becomes lower but basically still satisfactory.

Another interesting observation is that, when we compare the accuracy of the analytical models under short- and long-duration traffic respectively, there is no clear winner, though intuitively people may expect a lower accuracy under short-duration traffic. This can be explained as follows: the accuracy of the analytical models is mainly affected by the simplification assumptions that have been made (e.g., neighborhood-link correlation, independent attempting connections on different routes, etc.). Analysis of the cases under long-duration traffic is basically rather sensitive to these assumptions since most of the assumptions lower the accuracy of link-state calculations while link state directly decides the dominant forward blocking. Under short-duration traffic, backward blocking dominates, which to some extent is less sensitive to these assumptions since backward blocking is largely decided by the amount of outdated link-state information rather than directly by link state itself. Therefore, as long as we could correctly calculate the effects of outdated link-state information, it is actually not a surprise that a comparable, or even higher accuracy could be achieved in analyzing short-duration traffic cases.

Finally, we study the case where the number of wavelength channels in each fiber is increased from 8 to 16. Simulation results in PacNet and ring network are plotted in Fig. 3.11 and Fig. 3.12, respectively. To avoid having too many figures in this chapter, only the results for the case with a 100 ms average duration of connection have been presented. But the conclusions hold for all the other cases: the

Evaluation and Analysis of Distributed Parallel Reservations

(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 3. 11: Accuracy of the analytical models in PacNet under short-duration traffic with an average duration of connection of 100 ms. There are 16 wavelengths in each fiber.

Chapter 3

(a) 1P-1R and 1P-2R

(b) 2P-1R, 2P-2R, and 2P-4R

Fig. 3. 12: Accuracy of the analytical models in 12-node ring under short-duration traffic with an average duration of connection of 100 ms. There are 16 wavelengths in each fiber.

Evaluation and Analysis of Distributed Parallel Reservations

proposed models remain to be rather accurate; and having parallel reservations on multiple candidate routes remains to significantly improve network performance under light traffic loads.

3.4.3 Evaluations of the Control Overhead

To measure the control overhead of the different schemes, we plot in Fig. 3.13 control traffic of different schemes under different data traffic loads. Specifically, whenever there is a connection/reservation/release request passing through a link, we take into account one unit of “control traffic”. Since there is no standardized signaling protocol for parallel reservations, we make the exaggerative assumption that to reserve/release k ($k > 1$) wavelengths on a same route, we need k separate reservation/release messages. Fig. 3.13 shows for all the five different schemes the average number of control messages generated in every second under short-duration traffic with an average duration of connection of 100ms (Control traffic is generally not a big concern under long-duration traffic.). We see that though under light traffic loads, control overhead increases significantly with the increased number of candidate routes and increased number of reservations on each route, for a well-engineered network capable of handling heavy traffic loads for the classic DIR (i.e., 1P-1R) scheme, it is reasonable to expect that the control overhead of parallel reservations is acceptable. Under heavy traffic loads, since the chance of having multiple successful reservations becomes rather low, the control traffic is not increased quite significantly compared to the classic DIR scheme. Furthermore, considering the fact that different schemes perform comparable to each other under heavy traffic loads, we expect that some new schemes could be developed to switch back to 1P-1R operation under heavy traffic loads, such that the control overhead could be further lowered.

Chapter 3

Fig. 3. 13: The average number of control messages processed every second in PacNet under traffic with an average duration of connection of 100 ms.

Fig. 3. 14: The average number of control messages processed every second for 2P-2R in PacNet under traffic with different average durations of connection.

Evaluation and Analysis of Distributed Parallel Reservations

Note that the evaluations in Fig. 3.13 are based on the pessimistic assumption we made above. If we assume that parallel reservations/releases on a same route could be handled by a single message, then 1P-2R has nearly the same amount of control traffic as that of 1P-1R, and 2P-4R nearly the same as that of 2P-2R. On the other hand, 2P-2R would still has a higher control overhead than that of 1P-1R. Under such case, when control overhead is a major concern, 1P-2R may be a better choice than 2P-2R, though the latter one generally leads to better network blocking performance.

To measure the control overhead under traffic loads with different average durations of connection, we test the case of implementing 2P-2R scheme in PacNet. The simulation results are plotted in Fig. 3.14. As we can observe, control overhead increases quickly with a decreasing average duration of connection.

3.5 Conclusions

In this chapter we conducted a comprehensive evaluation of parallel reservation schemes for distributed lightpath establishment in wavelength-routed networks, using the MPPR scheme as a case study. We proposed widely applicable analytical models of which the accuracy has been verified by extensive simulations. Analytical and numerical results show that the parallel reservation schemes, with increased yet generally still moderate control overhead, can significantly improve network blocking performance under constantly-changing, low or medium traffic loads. We showed that parallel reservations on different routes generally perform better than making them on the same route, while too many parallel reservations may lead to serious over-reservations which actually degrade the network blocking performance.

4

Performance Evaluations of Distributed Lightpath Provisioning with Dynamic Routing and Wavelength Assignment

4.1 Introduction

In Chapter 2, we provided a literature survey of the existing solutions for lowering the impacts of outdated link-state information on distributed lightpath provisioning. A closer look at these existing results (including the MPPR scheme we have extensively studied in Chapter 3) shows that they are either for the case with only global information flooding where lightpath establishment decisions are made based on flooded information (e.g., [6, 7, 11]), or for the case with only local link-state information exchanges (e.g., [10, 13, 14, 23, 44]). In this chapter, we study a different case where global information flooding and local information exchanges co-exist in the same network which enables dynamic routing *and* wavelength assignment. Such a scheme can be implemented in real-life networks with existing technology. Specifically, we consider the case where (i) information flooding is done periodically at a relatively low frequency (such that the control overhead is not overwhelming). Based on the flooded information, dynamic routing decisions can be made; and (ii) wavelength assignment is decided based on locally-exchanged information. Without loss of generality, we study the case where local information exchange (and lightpath establishment) is implemented by the DIR method, as that in [10, 13]. Since

theoretical analysis of dynamic routing performance is notoriously difficult, we conduct the evaluations by extensive simulations. Numerical results show that, even when the flooding frequency is rather low, such schemes in most cases significantly outperform those schemes with only global or local information exchanges. Note that the main purpose of this study is provide detailed evaluations of the impacts of various factors including RWA algorithm, network topology, number of wavelengths per fiber, flooding interval and traffic load, etc. on distributed lightpath provisioning schemes with dynamic RWA, rather than proposing the best possible scheme belonging to this class. Such evaluations, as we believe, will benefit the future developments of efficient lightpath provisioning schemes.

The rest of this chapter is organized as follows: The schemes being studied are defined in Section 4.2. Detailed evaluation results are presented in Section 4.3. Finally, Section 4.4 concludes the chapter.

4.2 Distributed Lightpath Provisioning with Dynamic RWA

The Distributed Lightpath Provisioning schemes with Dynamic RWA (denoted as *DLP-D schemes* hereafter) discussed in this chapter share the same framework containing two critical components as follows.

- Periodic flooding: We assume that the latest link-state information is periodically flooded to all the network nodes. To simplify discussions, we ignore the effects of propagation delay by assuming that upon a flooding, each node gets updated link-state information immediately. This simplification is acceptable when the flooding period is much longer than the propagation delay along any route in the network.

Chapter 4

- **DIR-based lightpath establishment:** Upon the arrival of a request for setting a lightpath, the source node would decide on the route of the lightpath based on the (possibly outdated) global link-state information it has in its local database. Then the DIR scheme is activated on the selected route. Specifically, a connection request is forwarded to the destination node along the selected route, collecting the latest link-state information along the route. Based on the information it collects, the destination node would select an appropriate wavelength (if applicable), and send a reservation request to reserve the selected wavelength along the route. If no free wavelength is available along the route, or if the reservation request is blocked due to outdated information, the request for setting up a lightpath is regarded as being blocked and all the reserved capacities (if any) will be released immediately. Effects of propagation delay dominate network performance in wavelength-routed networks with short-duration connections [13]. In networks with long-duration connections (e.g., several orders longer than the average propagation delay between every pair of nodes), however, the effects are marginal and actually can be neglected. In this chapter, we consider the case with long-duration connections. For such case, the dominant effect of outdated information is that it may let the source node choose an invalid route with no available wavelength.

We evaluate several different most typical RWA algorithms within the DLP-D framework. Though most of them have been introduced in Chapter 2, for convenient reading, we provide their definitions below. For the routing schemes, we shall consider

- *Fixed shortest-path* (FSP) routing, where each lightpath always goes through the minimum hop-length route (i.e., the route going through the minimum number of links) between each pair of source-destination nodes. Apparently DLP-D schemes adopting fixed shortest-path method is equivalent to the classic DIR method [10, 13], which actually does not need global information flooding. In this chapter, we study such schemes for comparison purpose.
- *Dynamic shortest-path* (DSP) routing, where based on the flooded information, the shortest hop-length route with at least one available wavelength along the route is selected.
- *Alternative path* (AP) routing, where among several pre-set link-disjoint candidate routes, the shortest one with at least one available wavelength (according to the flooded information) along the route is selected. In this chapter, we simulate the case where the first, second and third shortest-path routes between each pair of source-destination nodes are chosen as the candidate routes. Note that in a sparse network, there may not be three link-disjoint routes between some source-destination node pairs. Under such case, we will find as many alternative routes as possible.
- *Least congestion path* (LCP) routing, where among several pre-set link-disjoint candidate routes, according to the flooded information the one with the least congestion level is selected. The congestion is measured by the number of available wavelengths along the route: a large number of available wavelengths denote a lower congestion level of the route. In this

Chapter 4

chapter, again we consider the case with up to three candidate routes between each pair of source-destination nodes.

For comparison purpose, we call the last three methods the *adaptive routing* method.

For the wavelength assignment schemes, we evaluate the classic *random* and *first-fit* wavelength assignments [1, 41, 81]. Specifically, in the former case, one of the available wavelengths along the route is randomly selected by the destination node; while in the latter case, the lowest-indexed available wavelength is selected.

Note that throughout this chapter, we assume that wavelength conversion is not available. Therefore a wavelength is available along a route means that this wavelength is free on *every* hop along the route.

4.3 Simulation Results and Discussions

The simulation studies include two different parts:

- The DLP-D schemes are compared with the corresponding schemes with only periodic flooding but no local information exchange (termed as *flooding-only* schemes hereafter) where lightpath reservation is directly initialized by the source node, based on the (possibly outdated) global information it has [11, 12]. Intuitively we would expect the DLP-D schemes to outperform flooding-only schemes. However, it is of research interest to investigate the significance of the benefits of local information exchanges in different networks with different numbers of wavelengths per fiber and different flooding intervals.

- Within the DLP-D framework, different RWA methods will be compared with each other, with mainly two objectives: (i) to figure out under what cases dynamic routing schemes outperform the FSP routing scheme. Such comparisons reveal the benefits of having global link-state information flooding; and (ii) to identify the best RWA methods for different scenarios

Throughout this chapter, we assume that lightpath establishment requests arrive from a Poisson process. The duration of each lightpath is exponentially distributed with an average of 100 seconds. The overall traffic loads on the networks therefore can be measured in the unit of Erlang. Note that as mentioned earlier, in this chapter we only study the case where each lightpath has an average duration much longer than the average propagation delay between every pair of nodes. Most of today's wavelength-routed networks belong to this case. For the case with a very short average duration such as that in wavelength-routed optical burst-switched (WR-OBS) networks [5, 82], frequent link-state flooding may impose a serious challenge by adding to the already quite heavy traffic of control messages. For such cases intelligent flooding schemes may have to be developed in order to reduce control traffic (e.g., [45]). Network performance under such schemes, however, is out of the scope of this thesis.

To evaluate the effects of global information flooding at different frequencies, four different cases will be simulated with flooding intervals equaling to 1, 10, 100 and 500 seconds respectively. To evaluate the effects of the numbers of wavelengths per fiber, we simulate two different cases where each fiber contains 8 and 32 wavelengths respectively.

We present the simulations results on two different network models as follows:

Chapter 4

- The PacNet network as shown in Fig. 3.3, where the numbers next to the links denote the link lengths in tens of kilometers; and
- A 4×4 mesh-torus network where the length of each link is 100 kilometers.

For each case, 10 rounds of simulations have been conducted where in each round no less than 10^5 connection requests have been simulated (A much larger number of connection requests have to be simulated under low traffic loads in order to achieve reliable results for calculating the very low blocking probabilities under such case.). We present the average values of these 10 round simulations. Counting of the number of blocked lightpath establishment requests is started only after the network has reached a stable status. To better represent real-life scenarios, we make the same assumptions as those in Chapter 3, which include (1) control messages are handled in the First-Come-First-Serve (FCFS) manner on each node, where the processing time of each connection/reservation/release request is 10 μ s; (2) parallel OXC [56], which handles multiple switching operations in parallel, is employed on each node, with a switching time of 500 μ s; and (3) each node always forwards a reservation request immediately after processing without waiting for the configuration of the local OXC, i.e., the Forward before XC (FBXC) scheme [56] is adopted. Note that since the duration of each connection is relatively long, in our experiences, we can actually greatly simplify the simulations without losing accuracy. Specifically, we can assume that as long as there is an available wavelength along the selected route, the lightpath establishment is always successful, and still get nearly the same results.

4.3.1 Comparisons Between the DLP-D Schemes and the Flooding-Only Schemes

We first compare the DLP-D schemes with the corresponding flooding-only schemes. Our experiences show that, in flooding-only schemes, different adaptive routing methods including AP, LCP and DSP lead to nearly the same performance.

FSP performs differently under light and medium traffic loads, as we shall see later. The two wavelength assignment methods also perform closely to each other. In other words, the performance of the flooding-only schemes appears to be not very sensitive to the RWA method adopted. This is because that the performance of such schemes is dominated by the effects of outdated link-state information. Different routing and wavelength assignment methods generally do not make significant differences in reducing such effects. To avoid presenting too many figures in a chapter, we present only the results for FSP and DSP routing methods and random wavelength assignment. Comparisons between different RWA methods within the DLP-D framework will be discussed later in the next subsection.

Figs. 4.1-4.2 show for the two different routing methods respectively the comparisons between the two schemes in networks with eight wavelengths per fiber. Note that the DLP-D scheme with the FSP routing actually does not need link-state information flooding (That is why the flooding interval of the DLP-D scheme is not specified in the Fig. 4.1.). The comparisons presented in Fig. 4.1 therefore are actually between the classic fixed-routing DIR method and the fixed-routing flooding-only scheme. As we can see, the DIR method significantly outperforms the flooding-only scheme under light traffic loads even when the latter one has a rather short flooding interval of just one second. The differences between them, however, decrease quickly

Chapter 4

(a) PacNet

(b) 4×4 mesh-torus network

Fig. 4. 1: Comparisons between the DLP-D and flooding-only schemes adopting the FSP routing method and random wavelength assignment. There are eight wavelengths per fiber.

Performance Evaluation of Distributed Lightpath Provisioning with Dynamic Routing and Wavelength Assignment

(a) PacNet

(b) 4x4 mesh-torus network

Fig. 4. 2: Comparisons between the DLP-D and flooding-only schemes adopting the DSP routing method and random wavelength assignment. There are eight wavelengths per fiber.

Chapter 4

under heavier traffic loads. For the case where an adaptive routing method such as DSP is adopted, as we can observe in Fig. 4.2, the DLP-D schemes enjoy a significant winning margin over the flooding-only schemes under not only light traffic loads, but also medium to high traffic loads especially when the flooding interval is long. Moreover, for both of the two routing methods, especially the DSP routing, the winning margin of the DLP-D schemes is more significant in the more densely-connected 4×4 mesh-torus network.

A comparison between Figs. 4.1 and 4.2 shows that in the flooding-only schemes, DSP outperforms FSP in both network models under light, but not too low (e.g., 10 Erlangs), traffic loads when the flooding interval is reasonably short (no more than 10 s). For the other cases, the differences between the two routing methods generally are not significant. This can be explained as follows: under light traffic loads, the two routing methods tend to select the same shortest-path route. Therefore the differences in their performances are trivial. Under too high traffic loads, blocking is mainly caused by exhausted network resources. Under medium traffic loads, DSP helps to achieve better load balancing and hence leads to better performance. When the flooding interval is too long, however, the overwhelming amount of outdated information makes intelligent routing decision-making based on it largely useless.

When there are 32 wavelengths per fiber, as we can see in Figs. 4.3-4.4, the winning margin enjoyed by DLP-D schemes becomes even larger. In fact, the blocking probabilities of DLP-D schemes in the mesh-torus network steadily stay below the range we have plotted. Hence there appear to be no curves showing the blocking probabilities of DLP-D schemes in Figs. 4.3(b) and 4.4(b).

Performance Evaluation of Distributed Lightpath Provisioning with Dynamic Routing and Wavelength Assignment

(a) PacNet

(b) 4x4 mesh-torus network

Fig. 4. 3: Comparisons between the DLP-D and flooding-only schemes adopting the FSP routing method and random wavelength assignment. There are 32 wavelengths per fiber.

Chapter 4

(a) PacNet

(b) 4×4 mesh-torus network

Fig. 4. 4: Comparisons between the DLP-D and flooding-only schemes adopting the DSP routing method and random wavelength assignment. There are 32 wavelengths per fiber.

Overall, the observation is that the DLP-D schemes significantly outperform the flooding-only methods even when the flooding interval is quite short. The winning margin is more significant when adaptive routing methods are adopted or in a more densely-connected network with a larger number of wavelengths per fiber.

4.3.2 Comparisons Between Different RWA Algorithms Within the DLP-D Framework

Within the DLP-D framework, we compare the performances of different RWA algorithms in different networks with different numbers of wavelengths per fiber and different flooding intervals.

Fig. 4.5 shows the results where there are eight wavelengths per fiber and the flooding interval is 1 s. We see that in a sparse network like PacNet, the FSP routing method performs the worst while the other routing methods perform comparably to each other. This is because that in a sparse network, FSP routing may cause a high congestion level on a few “bottleneck” links. The other routing methods, by achieving better load balancing between different links, solve this problem to some extent. In the densely connected mesh-torus network, however, LCP routing appears to be the best method under light traffic loads while DSP routing outperforms the others under heavy traffic loads. This can be explained: in mesh-torus networks, several candidate routes are of comparable (or even the same) lengths. LCP routing, by achieving the best load balancing among all the RWA methods we have evaluated, has the best performance. Under heavy traffic loads, the more important concern is to save network capacity resources as much as possible. Therefore DSP routing becomes more favorable. As to the comparisons between the two wavelength assignment

Chapter 4

(a) PacNet

(b) 4x4 mesh-torus network

Fig. 4. 5: Comparisons between different RWA methods where there are eight wavelengths per fiber and the flooding interval is 1 second.

Performance Evaluation of Distributed Lightpath Provisioning with Dynamic Routing and Wavelength Assignment

(a) PacNet

(b) 4x4 mesh-torus network

Fig. 4. 6: Comparisons between different RWA methods where there are 32 wavelengths per fiber and the flooding interval is 1 second.

Chapter 4

methods, the frequently available updated link-state information lets the first-fit method outperform the random method.

The above conclusions remain valid in networks where there are 32 wavelengths per fiber, though the differences between different routing and wavelength assignment methods generally become larger in the mesh-torus network, as we can observe in Fig. 4.6.

When the flooding interval is increased to 10 s, the chance of having outdated link-state information is also increased. However, the differences are not significant enough to change the above conclusions, except that the winning margin of the LCP routing method in densely-connected networks becomes more significant, enabling it to be the best routing method even under heavy traffic loads. This is because that LCP routing method, by selecting the route with the lowest congestion level, has the best tolerance to the slightly outdated link-state information. We only present in Fig. 4.7 the simulation results in networks with 32 wavelengths per fiber, while all the conclusions hold in networks with eight wavelengths per fiber. Comparing Figs. 4.6 and 4.7, it is not a surprise to see that the blocking probabilities under the same traffic loads go up, though generally not very significant.

When the flooding interval is further increased to be equal to the average transmission duration of 100 s, the most important observations include (1) most of the adaptive routing methods gradually lose their winning margin over the FSP routing method, especially in sparse networks, as we can observe in Figs. 4.8(a) and 4.9(a); and (2) LCP routing gradually lose its best performance to DSP routing scheme, especially in densely-connected networks, as we could see in Figs. 4.8(b) and

Performance Evaluation of Distributed Lightpath Provisioning with Dynamic Routing and Wavelength Assignment

(a) PacNet

(b) 4x4 mesh-torus network

Fig. 4. 7: Comparisons between different RWA methods where there are 32 wavelengths per fiber and the flooding interval is 10 seconds.

Chapter 4

(a) PacNet

(b) 4x4 mesh-torus network

Fig. 4. 8: Comparisons between different RWA methods where there are eight wavelengths per fiber and the flooding interval is 100 seconds.

Performance Evaluation of Distributed Lightpath Provisioning with Dynamic Routing and Wavelength Assignment

(a) PacNet

(b) 4x4 mesh-torus network

Fig. 4. 9: Comparisons between different RWA methods where there are 32 wavelengths per fiber and the flooding interval is 100 seconds.

Chapter 4

4.9(b). These observations can be explained: with a longer flooding interval, outdated information accumulates. Adaptive routing decisions made based on such information therefore become less effective. LCP routing, by selecting the route with the least congestion, tends to select longer routes than the other methods, which makes the effects of outdated information even more significant. LCP remains its winning margin in PacNet with 32 wavelengths per fiber (as we can see in Fig. 4.9(a)) because it helps to avoid overloading a few bottleneck links. Between the two different wavelength assignment methods, we find that first-fit wavelength assignment general still outperforms random assignment though the differences between them become much smaller. Comparing Figs. 4.8 and 4.9, we see that the blocking probability under the same traffic load *per wavelength* becomes lower with a larger number of wavelengths in each fiber. The existence of more wavelength channels still helps to lower blocking probability even when routing decisions are made based on seriously outdated information.

Finally when the flooding interval becomes much longer than the average connection duration, the observations become quite different: LCP routing method becomes the worst method due to the effects of the overwhelming amount of outdated information. Selecting a longer route under such case is no longer a favorable option. Other than the LCP method, all the other routing methods perform nearly the same in the sparse PacNet. DSP routing method still manages to outperform the others in the mesh-torus network though the winning margin is never significant. As to the wavelength assignment methods, random and first-fit methods perform comparably to each other under most cases. There is no clear winner between them. The above conclusions can be observed in Figs. 4.10 and 4.11.

Performance Evaluation of Distributed Lightpath Provisioning with Dynamic Routing and Wavelength Assignment

(a) PacNet

(b) 4x4 mesh-torus network

Fig. 4. 10: Comparisons between different RWA methods where there are eight wavelengths per fiber and the flooding interval is 500 seconds.

Chapter 4

(a) PacNet

(b) 4x4 mesh-torus network

Fig. 4. 11: Comparisons between different RWA methods where there are 32 wavelengths per fiber and the flooding interval is 500 seconds.

To summarize, the observations include that when flooding interval is short compared to the average duration of each connection, LCP is usually the best routing method in dense networks. The winning margin is larger where there are a larger number of wavelengths per fiber. In sparse networks, FSP is the worst one while the other routing methods generally speaking perform nearly the same. In lightpath provisioning with a long flooding interval, LCP becomes the worst routing method in all the different networks, while DSP performs the best in dense networks. Between the two different wavelength assignment methods, first-fit method has never performed inferior to the random method. Note that such an observation is quite different from that in lightpath provisioning for short-duration connections, where random assignment steadily performs better [7].

4.4 Conclusions

In this chapter, we studied the performance of the DLP-D schemes. It was revealed that DLP-D schemes, by combining global information flooding and local information exchange, significantly outperform the flooding-only schemes. As long as the flooding interval is not much longer than the average duration of each connection, DLP-D schemes perform better than the classic fixed-routing DIR scheme as well. Overall the winning margin is bigger in dense networks with a larger number of wavelengths per fiber. Within the DLP-D scheme framework, comparisons between different RWA methods have also been conducted. It was shown that LCP routing is probably the best option when flooding interval is short. When the flooding interval is much longer than the average duration of connections, however, LCP becomes the worst routing method. In dense networks, DSP may be a favorable option when flooding interval is long. Lastly, between the two wavelength assignment methods,

Chapter 4

first-fit method appears to be the better one under most cases. The above observations provided us some insights useful for the future developments of DLP-D schemes.

5

Efficient Wavelength Assignment Methods for Distributed Lightpath Restorations

5.1 Introduction

With the large bandwidth provided by optical fibers, network survivability becomes increasingly important: a single link or node failure, if not properly protected, may interrupt a large number of users. In the literature, tremendous efforts have been made to improve network survivability [15-22, 29, 83-88].

Network survivability is generally supported by protection or restoration schemes [17, 29]. In protection schemes, backup solutions are preplanned and pre-established to ensure full recovery and short reconnection delay (defined as the delay from the moment the failure happens to the moment the transmission is resumed). In restoration schemes, backup resources are searched and identified after the event of failure. Though restoration schemes cannot guarantee full recovery, they lower the network cost by increasing the capacity utilizations.

The protection and restoration may be link-based or path-based [29, 84]. In link-based schemes [29], upon a link failure, the affected connections are rerouted around the failed link. In path-based schemes [29], each affected connection is re-allocated to a backup route. Generally speaking, path-based schemes achieve higher capacity efficiency with easier implementations, while link-based schemes achieve shorter

Chapter 5

recovery time [17-18, 29, 83-84]. In this chapter, we study the wavelength assignment problem in path-based network restoration. In link-based restoration, since the backup lightpath usually reuses some wavelength channels of the original lightpath, wavelength assignment generally remains unchanged as that of the original one unless wavelength conversion exists.

Like the case in the lightpath provisioning, restoration operations can also be centralized- or distributed-controlled. In centralized schemes, a central controller supervises all the restoration operations. Having a single point of decision making helps achieve efficient utilizations of network resources, especially in small networks with highly static traffic where reconnection delay is acceptably short. In large networks with dynamic traffic, however, the centralized control may cause an over-long reconnection delay. Even worse, the central controller itself may become an overloaded and congested point. For such cases, distributed control, where restoration requests are handled by the affected nodes instead of the central controller, becomes a more favorable option [17, 22, 85].

Distributed restoration decisions can be made based on either global or local information. In global information-based schemes, link-state information is broadcast to all the relevant network nodes so that each node has sufficient information to make its decisions [7, 15, 16, 21, 86-89]. Though having more link-state information helps make intelligent decisions, frequent broadcasting may impose heavy control and traffic burdens on the network. In local information-based schemes [29], link-state information exchange is limited and happens only when necessary.

It is not a surprise that, just as the MPPR schemes and the DLP-D schemes which we have discussed in the previous chapters, both global and local information-

based distributed schemes can be seriously affected by the presence of inaccurate link-state information. Specifically, in global information-based schemes, mainly because of the time delay between broadcasts, some network nodes may make invalid restoration decisions based on stale link-state information [11-12, 90-91]. In local information-based schemes, multiple interrupted connections trigger multiple restoration requests, which may conflict against each other trying to reserve the same wavelength on the same link even when there are still plenty of idle capacities on the link. In this chapter, we call such kind of conflicts as *blind contentions*. Fig. 5.1 shows a simple example where there is a blind contention between two restoration operations. Note that the blind contention problem can be viewed as a special type of distributed lightpath provisioning problem tending to be more seriously affected by the existence of outdated link-state information: upon a link failure, usually there are a number of concurrent restoration operations, many of which may go through the same link in their backup routes.

Several methods have been proposed to solve the blind contention problem. In [29], wavelengths are partitioned into several subsets, each corresponding to an interrupted connection. Each restoration request searches for a wavelength in its own subset. By doing so, blind contentions are eliminated. However, since each restoration request is searching for a free wavelength in its own subset only, it may be blocked when there are still idle capacities in other subsets. Another method was proposed in networks with periodic flooding [21], where one of the affected nodes (e.g., an end node of the failed link) makes all the wavelength assignment decisions based on the flooded information and then notifies all the other nodes. In such a scheme, blind contentions are again eliminated. However, besides the need of frequent link-state updates, the delay caused by decision making and notifications may also be too long,

Chapter 5

Fig. 5 1: A simple example of having a blind contention on the link from node 2 to node 3.

especially when there are a large number of interrupted connections. In [92], a first-fit-TE wavelength-assignment scheme is proposed for optical burst switching (OBS) networks which can be adopted in network restoration. The main idea of the method is to let each switch be assigned a start wavelength, starting from which a switch can check through all the wavelengths in the first-fit manner and transmit a new burst on the first available wavelength. It is shown that by assigning different routes going through the same link with different start wavelengths, the probability of having blind contentions can be lowered.

In this chapter, we propose two new wavelength assignment methods for local link-state information-based distributed lightpath restoration. Similar to the first-fit-TE scheme in [92], they assign different restoration operations with different start wavelengths as well as predefined searching sequences. We call such methods as within the framework of the *Predefined Sequential Search* (PSS) schemes. The main and nontrivial difference between the first-fit-TE method and the proposed methods

lies in the searching sequence of each restoration operation: instead of adopting the first-fit manner, we devise different searching sequences for different restoration operations with the objective of minimizing the probability of having blind contentions. Simulation results evidently show that different searching sequences lead to significantly different performances. For the special case where there are only two restoration operations going through the same link and the lightpath establishment in the network has adopted random wavelength assignment, the optimality of the proposed methods among all the local information-based, fixed-routing PSS schemes can be proved. For a few most important more general cases (e.g., the case with random wavelength assignment in lightpath establishment yet three or more interrupted connections going through the same link; or with the first-fit wavelength assignment in lightpath establishment, etc.), we show that the optimality cannot be guaranteed by *any* PSS scheme with only local link-state information.

The rest part of this chapter is organized as follows. In Section 5.2, we propose the general framework of the PSS schemes, followed by detailed descriptions of the proposed methods. Theoretical analysis on the proposed methods is proposed in Section 5.3. Extensive simulation results and discussions are presented in Section 5.4. Section 5.5 concludes the chapter.

5.2 The Proposed Methods

In this section, we present the general framework of the PSS schemes, followed by detailed descriptions of two simple yet efficient PSS methods named *Flagged Search* (FS) and *Periodical Search* (PS) methods respectively.

Chapter 5

5.2.1 The Framework of the Predefined Sequential Search (PSS) Schemes

In the PSS schemes, each restoration operation searches through all the wavelengths in a predefined sequence and selects the first available one among them. If no available wavelength exists along the backup route or if the selected wavelength later turns out to be reserved by another reservation request arrived earlier, the restoration request will be blocked. To focus our discussions solely on wavelength assignment problem, in this chapter we consider the case in single-fiber networks where each connection has a single predefined backup route, though the scheme can be extended to apply in multi-fiber networks or networks with multiple or dynamic backup routes as well. We also assume that wavelength conversion is not available in the network.

The framework of the PSS schemes is presented as follows:

Predefined Sequential Search (PSS) Schemes: the Framework

1. *Initialization*: upon a link failure, the end nodes of each interrupted connection are informed.
2. *Link-state information collection*: the link-state information along the backup route is collected.
3. *Wavelength assignment*: based on the collected link-state information, a certain node, usually the source or the destination node of the interrupted connection, decides on the wavelength assignment. The method is to search through all the wavelengths in a pre-defined sequence and select the first available one among them. If no such wavelength exists, the restoration request is blocked.

4. *Setting up restoration lightpath*: A reservation request is sent out, typically by the source or the destination node, to reserve the selected wavelength along the backup route. Interrupted transmission is resumed once the restoration connection is set up. If the selected wavelength is occupied by another reservation request arrived earlier, however, the restoration request is blocked.

In the next subsection, we propose two simple yet representative and efficient PSS methods in details. The analysis of their performances and the optimality of them for a special case will be discussed in Section III.

5.2.2 The Two Proposed Methods

To simplify the descriptions, without loss of generality, we assume that each restoration request is initialized by the source node of the interrupted connection (Discussions on the signaling scheme for informing the source node upon a link failure can be found in [29].). A restoration request is then sent to the destination node along the backup route, collecting the link-state information along the route. Based on the collected information, the destination node would decide on the wavelength assignment and send a reservation request to reserve the selected wavelength. Communication will be resumed once the reservation request successfully reaches the source node. When a blind contention happens on a certain link, the downstream node of this link (i.e., the end node that is closer to the destination) will send out a *restoration failed* message to both the source and the destination. The reserved capacities meanwhile will be released. Note that the procedure is quite similar to the well-known destination-initialized reservation (DIR) method [10].

Chapter 5

Two restoration operations going through the same link have a blind contention on a wavelength w if and only if

- i. for each of them, all the wavelengths before w in its searching sequence have been occupied by lightpath establishment on one or multiple links along its backup route; and
- ii. wavelength w is free along both of the two backup routes.

The probability of event ii is not affected by searching sequence. To reduce blind contentions, we need to lower the probability of event i. Specifically, a wavelength at an early position in one searching sequence should be at a late position in the other sequences, so that the chance that the two operations select the same wavelength is lowered. This main idea applies to developing the proposed methods.

Both of the proposed methods are within the PSS framework. The only difference between them lies in their definitions of wavelength-searching sequences. Specifically, assume there are totally K ($K > 1$) interrupted connections, numbered from 1 to K in an increasing order of their *original* wavelength indexes. Denote the number of wavelengths in each fiber as C . The two different methods can be defined as follows.

Flagged Search (FS) method

We let K flags be *evenly* distributed within the interval $[1, C]$, where

$$FLAG_k = (k-1) \cdot \frac{C-1}{K-1} + 1, \quad k = 1, 2, \dots, K. \quad (5.1)$$

Note that each flag is not necessarily of an integer value. Upon a link failure, the k -th interrupted connection will search through all the wavelengths in an increasing

order of their *distances* from $FLAG_k$, where the distance between a wavelength w ($1 \leq w \leq C$) and $FLAG_k$ is defined as

$$d(w, FLAG_k) = \begin{cases} |w - FLAG_k|, & k = 1, K \\ \min(|w - FLAG_k|, C - |w - FLAG_k|), & \text{otherwise} \end{cases} \quad (5.2)$$

If there are two available wavelengths with the same distance from the flag, one of them will be randomly selected. For example, when $C = 8$ and $K = 4$, the four flags would be at $1, \frac{10}{3}, \frac{17}{3}$ and 8 respectively; and the searching sequences of the four restoration operations are

$$\begin{cases} Seq_1 = (1, 2, 3, 4, 5, 6, 7, 8) \\ Seq_2 = (3, 4, 2, 5, 1, 6, 8, 7) \\ Seq_3 = (6, 5, 7, 4, 8, 3, 1, 2) \\ Seq_4 = (8, 7, 6, 5, 4, 3, 2, 1) \end{cases} \quad (5.3)$$

When $C = 8$ and $K = 2$, the flags would be at 1 and 8 ; and the searching sequences are

$$\begin{cases} Seq_1 = (1, 2, 3, 4, 5, 6, 7, 8) \\ Seq_2 = (8, 7, 6, 5, 4, 3, 2, 1) \end{cases} \quad (5.4)$$

i.e., the two sequences are *reverse permutations* [93] to each other.

Periodically-Search (PS) method

In this method, we divide the wavelength set into K non-overlapping subsets where each subset contains lower- and higher-indexed wavelengths as evenly as possible. Specifically, the k -th subset contains the wavelengths

$$S_k = \{k, k + K, k + 2K, \dots, k + \lfloor (C - k) / K \rfloor K\}, \quad k = 1, 2, \dots, K. \quad (5.5)$$

Chapter 5

Here $\lfloor x \rfloor$ denotes the floor function of x , i.e., the largest integer not bigger than x .

Upon the link failure, the k -th interrupted connection will search for a free wavelength in S_k . If no feasible solution is found, it proceeds to search S_{k+1} if $k < K$ and S_1 otherwise. The procedure is repeated until a feasible solution is found or all the wavelengths have been searched. In other words, the subsets are searched sequentially in a round-robin manner. While searching through each subset, an “alternating searching sequence” is adopted. Specifically, it searches S_k in an increasing order of wavelength indexes, S_{k+1} (S_1 if $k = K$) in a decreasing order of wavelength indexes, S_{k+2} (S_1 if $k = K - 1$) in an increasing order again, and so on. The alternating searching sequence helps to lower the probability of having blind contentions. For example, when $C = 8$ and $K = 3$, the three subsets are

$$\begin{cases} S_1 = \{1, 4, 7\} \\ S_2 = \{2, 5, 8\} \\ S_3 = \{3, 6\} \end{cases} \quad (5.6)$$

And the three searching sequences are

$$\begin{cases} Seq_1 = (1, 4, 7, 8, 5, 2, 3, 6) \\ Seq_2 = (2, 5, 8, 6, 3, 1, 4, 7) \\ Seq_3 = (3, 6, 7, 4, 1, 2, 5, 8) \end{cases} \quad (5.7)$$

If the same searching sequence were used in every subset, then we would have

$$\begin{cases} Seq_1 = (1, 4, 7, 2, 5, 8, 3, 6) \\ Seq_2 = (2, 5, 8, 3, 6, 1, 4, 7) \\ Seq_3 = (3, 6, 1, 4, 7, 2, 5, 8) \end{cases} \quad (5.8)$$

If wavelengths $\{1, 4, 7\}$ are not available for the first restoration operation, its next five candidate wavelengths $\{2, 5, 8, 3, 6\}$ would be in exactly the same order as that of the first five candidate wavelengths of the second restoration operation. Meanwhile, if the third restoration operation cannot be set up on wavelengths $\{3, 6\}$, it will have the same searching sequence as that of the first restoration operation in the next six candidate wavelengths. The probability of having blind contentions therefore becomes higher.

When $C = 8$ and $K = 2$, the two subsets are

$$\begin{cases} S_1 = \{1, 3, 5, 7\} \\ S_2 = \{2, 4, 6, 8\} \end{cases} \quad (5.9)$$

and

$$\begin{cases} Seq_1 = (1, 3, 5, 7, 8, 6, 4, 2) \\ Seq_2 = (2, 4, 6, 8, 7, 5, 3, 1) \end{cases} \quad (5.10)$$

Once again the two sequences are reverse permutations to each other.

Remark: Compared to the classic first-fit wavelength assignment method, both of the proposed schemes request only one additional step for calculating the searching sequence. The complexity of this additional step is of a low value at $O(CK)$. $\square$

5.3 Theoretical Analysis

In this section, we propose a general model for analyzing the probability of having blind contentions. Then we prove that both the FS and PS methods achieve the optimality under the special conditions that (i) there are only two restoration requests

Chapter 5

going through the same link, and (ii) along the same backup route, different wavelengths have the same probability of being available (An example is where we adopt random wavelength assignment in lightpath establishment.). For a few most important more general cases, we show that *no* local information-based fixed-routing PSS scheme can guarantee to achieve the optimal performance.

The following notations are defined:

C the number of wavelengths in each fiber,

K the number of interrupted connections,

k the index of the restoration operation in an increasing order of their original wavelength indexes, $k = 1, 2, \dots, K$,

$\alpha_{k,j}$ the probability that the wavelength λ_j is available along the backup route of the k -th restoration operation, $j = 1, 2, \dots, C$,

M^k the searching sequence of the k -th restoration operation,
 $M^k = \{M_{(1)}^k, M_{(2)}^k, \dots, M_{(C)}^k\},$

$d_k(j)$ the position of λ_j in the searching sequence of the k -th restoration request, i.e., $M_{(d_k(j))}^k = j$,

$P_{k,j}$ the probability that the k -th restoration request selects the wavelength λ_j .

We have that

$$P_{k,j} = \begin{cases} \alpha_{k,j}, & \text{if } M_{(1)}^k = j \\ \prod_{i=1}^{d_k(j)-1} (1 - \alpha_{k,M_{(i)}^k}) \cdot \alpha_{k,j}, & \text{otherwise} \end{cases} \quad (5.11)$$

For the special case where $\alpha_{k,1} = \alpha_{k,2} = \dots = \alpha_{k,C} = \alpha_k$, we have

$$P_{k,j} = (1 - \alpha_k)^{d_k(j)-1} \cdot \alpha_k. \quad (5.12)$$

From the de Moivre-Jordan Theorem [80], the probability that a restoration request gets blocked, termed as *restoration blocking probability* hereafter, can be calculated as

$$P = \sum_{j=1}^C \sum_{k=2}^K (-1)^k \cdot (k-1) \cdot S_{k,j}, \quad (5.13)$$

where

$$S_{k,j} = \sum_{l_1 < \dots < l_k} \prod_{i=1}^k P_{l_i,j}. \quad (5.14)$$

Theorem 1: Assume that along the same backup route, different wavelengths have the same probability of being available. Also assume there are only two backup routes R_1 and R_2 going through the same link l , where the probabilities that each wavelength is available along these two routes equal to α_1 and α_2 respectively. The restoration blocking probability is minimized if and only if the two searching sequences are reverse permutations to each other.

Proof: For such case, from Eqs. (5.12)-(5.14), we have that the probability of having a blind contention between the two restoration operations is

Chapter 5

$$\begin{aligned}
P &= \sum_{j=1}^C (1 - \alpha_1)^{d_1(j)-1} \cdot \alpha_1 \cdot (1 - \alpha_2)^{d_2(j)-1} \cdot \alpha_2 \\
&= (1 - \alpha_1)^{-1} \cdot \alpha_1 \cdot (1 - \alpha_2)^{-1} \cdot \alpha_2 \cdot \sum_{j=1}^C (1 - \alpha_1)^{d_1(j)} \cdot (1 - \alpha_2)^{d_2(j)}.
\end{aligned} \tag{5.15}$$

Since $\{(1 - \alpha_i)^1, (1 - \alpha_i)^2, \dots, (1 - \alpha_i)^C\}$, $(i = 1, 2)$ form into a decreasing series, from the *permutation inequality* [93], we have

$$P \geq (1 - \alpha_1)^{-1} \cdot \alpha_1 \cdot (1 - \alpha_2)^{-1} \cdot \alpha_2 \sum_{m=1}^C (1 - \alpha_1)^{d_1(j)} \cdot (1 - \alpha_2)^{C+1-d_1(j)}. \tag{5.16}$$

The theorem is therefore proved. $\square$

Theorem 1 shows that the proposed FS and PS methods achieve the optimality when there are only two restoration operations going through the same link and the original lightpath establishment has adopted random wavelength assignment. For more general cases where

- i. the assumption remains valid that along the same backup route different wavelengths have the same probability of being available, yet there are three or more restoration requests going through the same link; or
- ii. different wavelengths along the same backup route may have different probabilities of being available,

we observe that

- with three or more restoration operations going through the same link, no predefined searching sequences can guarantee to achieve the best performance even when random wavelength assignment has been

adopted in the original lightpath establishment. The best wavelength assignment under such case is link-state dependent; and

with different wavelengths having different probabilities of being available along each backup route, the reverse permutation wavelength assignment does not always minimize the probability of having a blind contention between two restoration operations. The conclusion applies to the special case where the first-fit wavelength assignment has been adopted in lightpath establishment.

Examples demonstrating the above observations are presented as follows. First, we show that for the case where different wavelengths have different probabilities of being available along each backup route, e.g., where the first-fit wavelength assignment has been adopted in lightpath establishment, the reverse permutation wavelength assignment does not necessarily lead to the lowest probability of having a blind contention between two restoration operations.

Consider the example case where there are two restoration operations in a network with only two wavelengths $\{\lambda_1, \lambda_2\}$ on each link. Let the probabilities that the two wavelengths are available on the first backup route be $\{\alpha_{1,1}, \alpha_{1,2}\} = \{0.01, 0.9\}$; and on the second route be $\{\alpha_{2,1}, \alpha_{2,2}\} = \{0.02, 0.8\}$. As shown in Table 5.1, the lowest restoration blocking probability is achieved when both restorations adopt the same searching sequence $\{1, 2\}$. We then show that with three or more restoration operations going through the same link, the best searching sequences are link-state dependent even when the random wavelength assignment has been adopted in lightpath establishment. Specifically, we consider the case with three

Chapter 5

Table 5. 1: Calculation results for the case with two restoration requests, assuming

$$\{\alpha_{1,1}, \alpha_{1,2}\} = \{0.01, 0.9\} \text{ and } \{\alpha_{2,1}, \alpha_{2,2}\} = \{0.02, 0.8\}$$

$\{M_{(1)}^1, M_{(2)}^1\}$	$\{M_{(1)}^2, M_{(2)}^2\}$	P
$\{1, 2\}$	$\{1, 2\}$	0.698744
$\{1, 2\}$	$\{2, 1\}$	0.71284
$\{2, 1\}$	$\{1, 2\}$	0.70562
$\{2, 1\}$	$\{2, 1\}$	0.720004

Table 5. 2: Optimal solutions for example cases with three restoration requests and random wavelength assignment in lightpath establishment.

$\{\alpha_1, \alpha_2, \alpha_3\}$	$\{M_{(1)}^1, M_{(2)}^1, M_{(3)}^1\}$	$\{M_{(1)}^2, M_{(2)}^2, M_{(3)}^2\}$	$\{M_{(1)}^3, M_{(2)}^3, M_{(3)}^3\}$	P
$\{0.1, 0.2, 0.3\}$	$\{1, 2, 3\}$	$\{1, 2, 3\}$	$\{3, 2, 1\}$	0.195
$\{0.2, 0.6, 0.3\}$	$\{1, 3, 2\}$	$\{1, 3, 2\}$	$\{2, 3, 1\}$	0.389
$\{0.15, 0.45, 0.78\}$	$\{1, 2, 3\}$	$\{2, 1, 3\}$	$\{2, 3, 1\}$	0.370
$\{0.21, 0.9, 0.67\}$	$\{1, 3, 2\}$	$\{3, 1, 2\}$	$\{3, 2, 1\}$	0.383
$\{0.97, 0.91, 0.98\}$	$\{2, 1, 3\}$	$\{1, 2, 3\}$	$\{1, 3, 2\}$	0.132

restoration requests in a network with three wavelengths per fiber. Table 5.2 shows that for different link states, the optimal solution of searching sequences is different. Therefore no pre-defined search sequences can guarantee to achieve the optimal performance.

From the above examples, the important conclusion is that, for the most popular cases of adopting random or the first-fit wavelength assignments in lightpath establishment, the optimal performance of lightpath restoration cannot be guaranteed by any PSS schemes without link-state information exchange. On the other hand, as later we will demonstrate in Section 5.4, though without any such kind of information exchange, the proposed methods nevertheless manage to achieve satisfactory performance under most cases.

5.4 Numerical Simulations and Discussions

To evaluate the performance of the proposed methods, we conduct simulations in three different network models:

- PacNet as illustrated in Fig. 3.3 where each number next to the link denotes the length of the link in tens of kilometres. Again it is the same network as what we have applied in numerical simulations in Chapters 3 and 4;
- A 12-node ring network, where the length of each link is 100 km; and
- A 4×4 mesh-torus network, where the length of each link is 100 km.

In each network, we assume that each link is composed of two directional fibers of opposite directions with 64 wavelength channels per fiber (Note that cases with 32 and 128 wavelengths per fiber have also been simulated. All the conclusions we present below appear to hold in these two cases as well.). We also assume that the original lightpath establishment is on the route with the minimum number of hops between source-destination nodes, i.e., the route with the shortest hop length. The backup route is the shortest hop-length path that is link-disjoint to the route of the

Chapter 5

original lightpath. When there is a tie in route selection (i.e., there are multiple routes with the same hop length), break it randomly. The processing delay for handling each restoration/reservation request on each node is assumed to be equal to 10 microseconds.

For each given traffic load, we let the connection requests be arriving from a Poisson process with an exponentially-distributed duration. The average duration of each connection is one hour. We simulate a large-enough number of connection requests until the network has reached a stable status (i.e., the blocking probability converges). Then we tear down each link in turn and simulate all the restorations. The performance of the different wavelength assignment methods is evaluated by the restoration blocking probability.

We compare several different restoration wavelength assignment methods as follows:

- a) *Random* wavelength assignment, where according to the information carried to the destination node by the restoration request, one of the available wavelengths along the backup route is randomly selected.
- b) *Partitioning* wavelength assignment as proposed in [29], where wavelengths are partitioned equally among all the restoration operations. This method was discussed for the case with multiple candidate backup routes in [29]. Here for comparison purpose, we assume that there is only a single backup route for each lightpath.

- c) The *first-fit-TE* method [92]. As discussed earlier, though the method was not proposed for restoration case, it can be applied to such case without any modification.
- d) The *centralized* method where there is a central controller making all the wavelength assignment decisions. Specifically, we sort all the restoration requests in an increasing order of the hop lengths of their backup routes. Then for each of them, we adopt the first-fit wavelength assignment along its backup route. This case provides a benchmark as an “upper bound” of the performance that a distributed wavelength assignment method can reasonably expect to achieve.
- e) The proposed FS method.
- f) The proposed PS method.

For each case, we repeat the simulations for ten times by using different seeds in random-number generations and then present the average results of these ten rounds of simulations.

We first consider the case where the original lightpath establishment has adopted random wavelength assignment. The simulation results in the three networks are presented in Figs. 5.2-5.4 respectively. From the simulation results, we observe that the proposed methods almost always outperform the existing ones; and the improvements tend to become more significant under lower traffic loads with more redundant network resources for wavelength-assignment selections. That is because that under such case, restoration blocking mainly comes from blind contentions. The proposed method, by lowering the chance of having blind contentions, improves the

Chapter 5

Fig. 5 2: Restoration blocking probability in PacNet, while the original lightpath establishment has adopted random wavelength assignment.

Fig. 5 3: Restoration blocking probability in the 12-node ring network, while the original lightpath establishment has adopted random wavelength assignment.

Fig. 5.4: Restoration blocking probability in the 4x4 mesh-torus network, while the original lightpath establishment has adopted random wavelength assignment.

network performance. Under heavy traffic loads, restoration blocking is mainly caused by exhausted network capacities rather than blind contentions. Thus all the different methods perform comparably to each other (The only exception happens in the mesh-torus network in which the centralized method performs much better, as we will discuss later). More specifically, in PacNet (Fig. 5.2) and the ring network (Fig. 5.3), the performances of the proposed methods can be close to that of the centralized method. In the mesh-torus network (Fig. 5.4), however, the centralized method performs much better. This is because in the centralized method, the restoration requests are sorted in an increasing order of the hop lengths of their backup routes. As a result, almost all the restoration requests with short backup routes are successfully accepted (at the cost of those restorations with long backup routes), which is not the case in the distributed methods. In sparse networks such as PacNet and ring, the

Chapter 5

backup routes are generally with quite long hop lengths, leaving the centralized method a less significant winning margin over the distributed methods.

Under medium traffic loads, comparing Figs. 5.2 and 5.3, we see that it is more difficult for the proposed methods to perform nearly the same as the centralized method in ring network than in PacNet. This is easily to understand: while all the restoration requests are going through the same route in a ring network, it becomes highly difficult to eliminate the effects of blind contentions even by using the proposed method.

Other important observations include

- In all the three networks, the FS and PS methods always perform comparably to each other.
- The partitioning method performs quite well under low traffic loads. In fact, in all three networks, it outperforms both the random and first-fit TE methods under low traffic loads. Under high traffic loads, since each partition of wavelengths becomes a small set, some restorations may not be able to find a feasible solution though there are still free wavelengths in other partitions. Consequently the method becomes less attractive. A good method may be developed by adopting the partitioning method only under low traffic loads or only in restoring those lightpaths going through a lightly-loaded link. Detailed discussions on such a method, however, are out of the scope of this chapter.
- Under light traffic loads, since the first-fit-TE method adopts the round-robin searching sequence for every restoration request, it is not a surprise

that it is outperformed by the proposed methods. This evidently shows the significance of the differences in restoration performance different searching sequences can make. Under heavy traffic loads, as discussed earlier, all the different methods finally perform nearly the same, dominated by the effects of exhausted network capacities.

We then simulate the case where the original lightpath establishment adopts the first-fit wavelength assignment. The results are plotted in Figs. 5.5-5.7. As we can see, in all the three networks, the PS method significantly outperforms the FS method under light traffic loads. The reason is easy to understand: in the FS method, a few restoration operations would search through most or even all the lower-indexed wavelengths before starting to search higher-indexed wavelengths. Since lower-indexed wavelengths have been heavily utilized by lightpath establishment, the chance that these restoration operations would compete for the same wavelength becomes rather high. The PS method, on the other hand, searches through higher- and lower-indexed wavelengths in a more balanced manner. As a result, the chance of having blind contentions is significantly lowered. This also explains why even the random restoration wavelength assignment in many cases outperforms most of the existing methods. Also, under such case, the advantages of having global information become more significant. In fact, the PS method appears to be the only distributed wavelength assignment method that can come close to the centralized method even in sparse networks. To summarize, we see that when the first-fit wavelength assignment is adopted in lightpath establishment, a good wavelength assignment scheme for distributed lightpath restoration has to ensure that higher-indexed wavelengths appear reasonably early in each wavelength-searching sequence. Meanwhile, the basic rule remains valid that a wavelength appearing at an early position in one searching

Chapter 5

Fig. 5 5: Restoration blocking probability in PacNet, while the original lightpath establishment has adopted the first-fit wavelength assignment.

Fig. 5 6: Restoration blocking probability in the 12-node ring network while the original lightpath establishment has adopted the first-fit wavelength assignment.

Fig. 5.7: Restoration blocking probability in the 4x4 mesh-torus network, while the original lightpath establishment has adopted the first-fit wavelength assignment.

sequence should appear at a late position in the others searching sequences as far as such is possible.

Another interesting observation is that the partitioning method remains as the worst one under most cases, steadily outperformed by random wavelength assignment method. This is not a surprise since the first few partitions in the partitioning method are heavily loaded with high blocking probabilities.

5.5 Conclusions

In this chapter, within the same framework of the PSS schemes we proposed two efficient wavelength assignment methods for lowering the restoration blocking probability. Simulation results showed that under most cases they significantly outperform the existing methods. Theoretical analysis confirmed the optimality of the

Chapter 5

proposed methods for a special case; while for a few most important more general cases, it was revealed that the optimal performance cannot be guaranteed by any local information-based fixed-routing PSS scheme. We evaluated different cases where lightpath establishment has adopted random and first-fit wavelength assignment methods respectively. It is shown that the latter one imposes additional constraints on the developments of distributed restoration schemes.

6 Conclusions

6.1 Summary of Main Contributions

Distributed lightpath provisioning is expected to play a key role in the next-generation wavelength-routed networks. A major challenge in distributed lightpath provisioning is the potentially significant degradation of network blocking performance caused by outdated link-state information, occurring especially under light traffic loads with short average durations of connections.

In this thesis, we reviewed the studies on distributed lightpath provisioning in wavelength-routed optical networks, with a main focus on the major challenges and existing solutions.

To better understand the impacts of outdated link-state information on the performance of distributed lightpath provisioning schemes, we firstly evaluated the performance of various distributed parallel reservation schemes in wavelength-routed networks by developing general yet accurate analytical models and conducting extensive simulations. Analytical and numerical results showed that by using simple parallel reservation schemes, in particular through multiple reservations on several different routes, blocking probabilities caused by outdated link-state information can be drastically lowered and network performance can be significantly improved. The

Chapter 6

tradeoff between control traffic loads and network blocking performance has also been evaluated.

We then examined the benefits of combining low-frequency global information flooding and upon-request local link-state information exchanges. Effects of various factors including RWA algorithm, network topology, number of wavelengths per fiber, flooding interval and traffic load, etc. on the proposed solutions were also carefully evaluated. We showed that the proposed schemes steadily outperform those existing schemes with only global flooding or only local information exchanges. In different scenarios, different routing methods perform quite differently. As long as the durations of connections are long enough, however, the first-fit wavelength assignment method would rather steadily remain as the winner over the random method.

In the last part of our research, we focused on developing efficient wavelength assignment schemes for distributed lightpath provisioning. Specifically, we proposed a new framework of distributed wavelength assignment schemes where each connection request is handled by searching through all the wavelengths in a pre-defined sequence. Two different methods have been proposed within the framework. By using the difficult distributed lightpath restoration problem as a case study, the proposed methods have been carefully evaluated. Theoretical analysis confirmed the optimality of the proposed methods for a special case; while for a few most important more general cases, it was revealed that the optimal performance cannot be guaranteed by any local information-based fixed-routing scheme within the proposed framework. Simulation results evidently demonstrated that under most cases the proposed methods significantly outperform the existing ones.

Conclusions

6.2 Future Research Directions

To design more efficient and realistic distributed wavelength provisioning schemes, several research topics are of our future research interest. They include

- Effects of limited-range wavelength conversion. Effects of sparse wavelength conversion in distributed lightpath provisioning have been evaluated [94] yet the performance of the limited-range wavelength conversion in such cases remains largely unknown. Our studies in Chapter 5 imply that in order to achieve satisfactory performance, some new wavelength assignment methods probably need to be developed for such cases.
- Implementations of the proposed schemes within the GMPLS framework. Though it is widely accepted that the SIR and DIR methods can be supported within the GMPLS framework, control and signaling schemes for MPPR methods still need to be carefully developed, especially if they are supposed to be integrated with some newly proposed wavelength assignment schemes (such as those proposed in Chapter 5).
- Distributed wavelength provisioning in multi-fiber networks. While it is well-known that having multiple fibers in each link helps to significantly lower the impacts of the wavelength continuity constraint on centralized lightpath provisioning schemes [95-98], efficient distributed lightpath provisioning in multi-fiber WDM networks remains largely an open area. New schemes have to be developed and carefully evaluated. New node architectures may also have to be developed: though some cost-effective node architectures have been proposed and demonstrated to achieve satisfactory performances in

Chapter 6

centralized schemes [99-100], it is not clear whether they work for distributed lightpath provisioning without accurate global link-state information.

We will study the above topics in our future research. In the long-term future, quality of service (QoS) by distributed lightpath provisioning and integrated packet-circuit communications in WDM networks may be of our research interest.

Author's Publications

1. G. Xiao and J. Liu, "Multi-Path Parallel Reservation Scheme for Distributed Lightpath Establishment in Wavelength-Routed WDM Networks," *Proc. ECOC'2003*, Vol. 3, pp. 842-843, Sept. 2003.
2. J. Liu and G. Xiao, "An Efficient Wavelength Assignment Method for Distributed Lightpath Restoration in Wavelength-Routed Networks," *Proc. ICICS'2007*, Dec. 2007.
3. J. Liu, G. Xiao, K. Lu, and I. Chlamtac, "An Evaluation of Distributed Parallel Reservations in Wavelength-Routed Networks," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 9, pp. 27-39, Dec. 2007.
4. J. Liu and G. Xiao, "Efficient Wavelength Assignment Schemes for Distributed Lightpath Restorations in WDM Networks," *IEEE/OSA Journal of Lightwave Technology*, in press.
5. J. Liu, G. Xiao, and W. Wang, "On the Performance of Distributed Lightpath Provisioning with Dynamic Routing and Wavelength Assignment", *Photonic Network Communications*, accepted for publication.

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