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Intelligent Control of Reconfigurable Optical Add Drop Modules in Agile Metropolitan Network Environments

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Abstract

With the even faster popularity of multimedia applications in recent years, newly emerging applications require short-lived high bandwidth connections. The agile all-optical solution is one approach to setting up a solid supporting layer for the next-generation Ethernet-based communication network infrastructure. In agile all-optical networks, time division multiplexing (TDM) in the optical domain is applied on wavelength channels to further divide each wavelength channel into subchannels. This approach enables *bandwidth virtualization* where the bandwidth allocation for network traffic demands is decoupled from wavelength channels, supporting a variety of data rates ranging from sub-wavelength to super-wavelength.

The objective of this thesis is to design a fast and smart control mechanism to manage the connection operations in agile all-optical networks by using analytical and simulation tools. This thesis focuses on the control of dynamic and flexible traffic in *metro* networks and covers the following aspects of the control plane: *bandwidth allocation*, which includes route selection and fiber, wavelength and timeslot assignment for flexible bandwidth demands aiming to minimize connection blocking; *signaling and reservation*, which is responsible for network information exchange and node switching control in order to manage connections effectively; and *network protection and restoration*, which is able to maintain the continuity of critical network services in the presence of network failures. In this work, network blocking performance is chosen as the key metric in measuring the performances of algorithms and protocols for dynamic traffic control.

The proposed algorithms and protocols are evaluated by the definition of mathematical and simulation models through which the best approaches under different network conditions are identified. The algorithms, protocols and analytical and simulation models resulting from this thesis can be used to understand the different aspects of dynamic traffic control in agile all-optical networks, to predict the performance of some control mechanisms to be deployed in agile all-optical networks, and as a reference for the design of next-generation all-optical networks.

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Statement of Originality

The work presented in this thesis was performed at the Photonic Technology Laboratory in the Centre for Research in Photonics at the University of Ottawa. The research was carried out under the supervision of Dr. Trevor J. Hall and the co-supervision of Dr. Henry Schriemer.

I declare that, to the best of my knowledge, the work presented in this thesis is original except where due acknowledgement is made in the text of the thesis. Furthermore, this work has not been submitted either whole or in part, for a degree at this or any other university. The results presented in this thesis were designed and derived by me during the period of my Ph.D. Some part of the work in the thesis has led to paper publications.

List of Previous Publications

Wei Yang, Sofia A. Paredes, Trevor J. Hall, "A Study of Fast Flexible Bandwidth Assignment Methods and their Blocking Probabilities for Metro Agile All-optical Ring Networks," IEEE International Conference on Communications (ICC 2007), pp 2418-2423, Glasgow, Scotland, 24-28 June 2007.

Wei Yang, Sofia A. Paredes, Trevor J. Hall, "The Impact of Stale Information on the Blocking Performance of Dynamic Routing, Wavelength and Timeslot Assignment Schemes for Bandwidth on Demand in Metro Agile All-Optical Ring Networks," SPIE Photonics North 2007, Ottawa, Canada, June 3-7, 2007.

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Table of content

Abstract i
Acknowledgements ii
Statement of Originality iii
Table of content v
List of Figures viii
List of Tables xi
List of Symbols xii
Ch. 1 Introduction 1
Ch. 2 Background 12
2.1 Agile all-optical networks 12
2.2 Routing algorithms 13
2.3 Wavelength and Timeslot assignment methods 15
2.4 Blocking Analysis 18
2.5 Signaling and reservation 20
2.5.1 Signaling and reservation with global information 21
2.5.2 Signaling and reservation without global information 23
2.6 Optical layer survivability 24
2.7 Survivability measures 26
2.8 SONET/SDH vs. next-generation all-optical networks 28
Ch. 3 Network Architecture 31
3.1 Basic Assumptions 31
3.2 Node architecture and network topology 32
3.3 Network model and traffic model 35
Ch. 4 Flexible Bandwidth Allocation 37
4.1 A DRWTA algorithm in single-fiber metro ring networks 37
4.1.1 Computational problem formulation 39
4.1.2 Distributed DRWTA algorithm 39
4.1.3 Simulation and analysis 43
4.1.4 Optimization criterion in the distributed DRWTA algorithm 46

4.2 Analytical model for single-fiber networks 54
4.2.1 Analytical model and initial values 55
4.2.2 Algorithm for computing network blocking probability 59
4.2.3 Comparison of analytical and simulation results 59
4.3 Heuristic algorithms for multi-fiber networks 61
4.3.1 A fiber designation scheme 62
4.3.2 Fiber, wavelength and timeslot assignment schemes 63
4.4 Least-Loaded algorithms for multi-fiber networks 69
4.5 Concluding remarks 74
Ch. 5 Signaling and Reservation 76
5.1 Control protocols with global information 78
5.1.1 Periodic link-state update protocol 79
5.1.2 Simulations for periodic update protocol 82
5.1.3 Triggered link-state update protocol 91
5.1.4 Simulations for triggered update protocol 94
5.1.5 Comparison of periodic update protocol and triggered update protocol 104
5.2 Control protocol without global information 108
5.2.1 Backward reservation protocol 108
5.2.2 Simulations for backward reservation protocol 112
5.2.3 Comparison of triggered update and backward reservation protocols ... 117
5.3 Concluding remarks 120
Ch. 6 Optical Layer Survivability 122
6.1 Optical survivability for agile all-optical metro rings 124
6.2 Blocking in single-duct ring networks with protection 127
6.2.1 Protection scheme for single-duct rings 127
6.2.2 Rearrangement 128
6.3 Blocking in dual-duct ring networks with protection 136
6.3.1 Protection scheme for dual-duct rings 137
6.3.2 Redundancy comparison of single- and dual-duct rings 139
6.3.3 Availability comparison of single- and dual-duct rings 144
6.4 Concluding remarks 146

Ch. 7 Conclusion 148
7.1 Summary 148
7.2 Suggestions for future work 154
References 157
Appendix 1. Program Codes of Simulation Models 164

List of Figures

Fig. 3.1 Node Sketch 33

Fig. 3.2 Network Model 35

Fig. 4.1. Blocking probability vs. network load. 44

Fig. 4.2. Blocking probability vs. number of nodes 44

Fig. 4.3. Blocking probability vs. number of wavelengths per fiber. 45

Fig. 4.4. Blocking probability vs. number of timeslots per frame 45

Fig. 4.5. Blocking probabilities: quasi-analytical and simulation results for W=8 T=8... 60

Fig. 4.6. Blocking probability of indexed fiber designation compared to random fiber assignment 63

Fig. 4.7. Blocking probability of fiber assignment schemes, all followed by random wavelength assignment. 66

Fig. 4.8. Blocking probability of wavelength assignment schemes, all preceded by random fiber assignment. 67

Fig. 4.9. Blocking probability of Least-Loaded algorithms 73

Fig. 4.10. Comparison of blocking probability of Least-Loaded algorithms and previous algorithms. 73

Fig. 5.1. Blocking probabilities of FF and RR algorithms for 16-node ring and 24-node ring, update period = 0.01. 83

Fig. 5.2. Blocking probabilities of FF and RR algorithms for 16-node ring and 24-node ring, update period = 0.1. 84

Fig. 5.3. Blocking probabilities of RR and RRS algorithms for 16-node ring and 24-node ring, update period = 0.1. 84

Fig. 5.4. Comparison of blocking probabilities, FF algorithm, 16-node ring, different update periods. 85

Fig. 5.5. Comparison of blocking probabilities, RR algorithm, 16-node ring, different update periods. 85

Fig. 5.6. Probabilities of the blocking caused by setup failures with FF and RR algorithms for 16-node ring, update period = 0.01, 0.1. 86

Fig. 5.7. Probabilities of the blockings caused by RWTA failures with FF and RR algorithms for 16-node ring, update period = 0.01, 0.1. 87

Fig. 5.8. Compositions of blocking probabilities, RR algorithm, 16-node ring, update period = 0.01. 88

Fig. 5.9. Compositions of blocking probabilities, RR algorithm, 16-node ring, update period = 0.1. 88

Fig. 5.10. Update ratio for periodic link-state update protocol with FF or RR algorithm, 16-node ring, update period = 0.01, 0.1. 89

Fig. 5.11. Comparison of update ratio for periodic link-state update protocol, RR algorithms, 16-node ring, different update periods. 90

Fig. 5.12. Blocking probabilities of FF and RR algorithms for 16-node ring and 24-node ring, trigger threshold = 0.25. 94

Fig. 5.13. Blocking probabilities of FF and RR algorithms for 16-node ring and 24-node ring, trigger threshold = 2.0. 95

Fig. 5.14. Comparison of blocking probabilities, FF algorithm, 16-node ring, different trigger thresholds. 96

Fig. 5.15. Probabilities of the blocking caused by setup failures, FF algorithm, 16-node ring, different trigger threshold. 97

Fig. 5.16. Probabilities of the blocking caused by RWTA failures, FF algorithm, 16-node ring, different trigger threshold. 97

Fig. 5.17. Comparison of blocking probabilities, RR algorithm, 16-node ring, different trigger thresholds. 99

Fig. 5.18. Probabilities of the blocking caused by setup failures, RR algorithm, 16-node ring, different trigger threshold. 99

Fig. 5.19. Probabilities of the blocking caused by RWTA failures, RR algorithm, 16-node ring, different trigger threshold. 99

Fig. 5.20. Compositions of blocking probabilities, RR algorithm for 16-node ring, trigger threshold = 0.25. 101

Fig. 5.21. Compositions of blocking probabilities, RR algorithm for 16-node ring, trigger threshold = 2.0. 101

Fig. 5.22. Update ratio for triggered link-state update protocol with FF or RR algorithm, 16-node ring and 24-node ring, trigger threshold = 0.25. 102

Fig. 5.23. Update ratio for triggered link-state update protocol with FF or RR algorithm, 16-node ring and 24-node ring, trigger threshold= 2.0. 102

Fig. 5.24. Comparison of update ratio for triggered link-state update protocol, FF or RR algorithm, 16-node ring, different trigger thresholds. 103

Fig. 5.25. Comparison of update ratio for periodic and triggered link-state update protocols, Period = 0.01, trigger threshold = 0.5 RR algorithms, 16-node ring. 105

Fig. 5.26. Comparison of blocking probabilities for periodic and triggered link-state update protocols, Period = 0.01, trigger threshold = 0.5 RR algorithms, 16-node ring. 105

Fig. 5.27. Blocking probabilities of the FF and RR algorithms for 16-node and 24-node rings, mean service time = 10 seconds. 113

Fig. 5.28.Comparison of blocking probabilities, FF algorithm, 16-node ring, different mean service times. 113

Fig. 5.29. Compositions of blocking probabilities, FF algorithm, 16-node ring, MST=1. 114
Fig. 5.30. Compositions of blocking probabilities, FF algorithm, 16-node ring, MST=10. 115
Fig. 5.31.Comparison of blocking probabilities, RR algorithm, 16-node ring, different mean service times. 115
Fig. 5.32. Compositions of blocking probabilities, RR algorithm, 16-node ring, MST=1. 116
Fig. 5.33. Compositions of blocking probabilities, RR algorithm, 16-node ring, MST=10. 116
Fig. 5.34. Comparison of blocking probabilities for the instant update with FF & no propagation delay, the triggered link-state update protocol with trigger threshold = 0.5 using adaptive RR+FF, and the backward reservation protocol with FF, mean service time = 10 seconds, 16-node ring. 118
Fig. 5.35. Comparison of the blocking caused by setup failures for the triggered link-state update protocol with trigger threshold = 0.5 using adaptive RR + FF, and the backward reservation protocol using FF, mean service time = 10 seconds, 16-node ring. 118
Fig. 6.1. Compositions of blocking probabilities for NoR and RTH. 133
Fig. 6.2. Blocking probabilities in single- and dual-duct networks with equal network capacity and equal amount of primary traffic load. 141
Fig. 6.3. Blocking probabilities in single- and dual-duct networks with equal network capacity and equal amount of network traffic load. 142
Fig. 6.4. Network capacity utilizations in single- and dual-duct networks with equal network capacity and equal amount of network traffic load. 143
Fig. 6.5. Blocking probabilities in single- and dual-duct networks, dual-duct networks double the network capacity and fourfold the amount of primary traffic load in single-duct networks. 144
Fig. 6.6. Network capacity utilizations in single- and dual-duct networks, dual-duct networks double the network capacity and fourfold the amount of primary traffic load in single-duct networks. 144

List of Tables

Table 4.1 Rates of demand distribution among 1 million demands 47

Table 4.2 Blocking probabilities of the DRWTA algorithm with the four criteria 52

Table 4.3 The maximum number of live connections in networks.................................. 52

Table 4.4 Rates of all-on-residual demands.. 53

Table 4.5 Rates of all-on-residual and partial-on-residual demands 53

Table 4.6 Blocking probabilities of the First-Fit and the DRWTA algorithms 53

Table 4.7 Blocking probability of the combination algorithms of packed assignment schemes 68

Table 6.1 Blocking probability for networks with or without rearrangement 133

Table 6.2 Probabilities of blocking during the bandwidth allocation for either primary or backup lightpaths. 135

Table 6.3 Comparison of probabilities of successful rearrangement and probabilities of total blocking. 136

List of Symbols

N	number of nodes in a network
F	number of fibers in a link
W	number of wavelengths per fiber
T	number of timeslots per TDM frame
λ	mean arrival rate of connection requests
$1/\mu$	mean service time of connection requests
e_t	set of residual wavelengths at stage t
a_t	set of available wavelengths on the link of hop t
g_{WL}	set of wavelengths occupied in the network
f_t	set of residual timeslots at stage t
b_t	set of available timeslots for wavelength under investigation on hop t
g_{TS}	set of timeslots used on wavelengths in the network, global information
R_w	the number of residual timeslots in wavelength w on the shortest path p
S_{NRW}	set of non-residual wavelengths on the shortest path p
S_{RW}	set of residual wavelengths on path p that have sufficient residual timeslots
S_{WR}	set of wavelengths on path p that have enough number of idle timeslots
L_w	total load of the first t residual timeslots of a wavelength
Pb_i	network blocking probability at iteration i
R	network redundancy
U	the unavailability of each link in a duct
U_c	the unavailability of a protected connection
A_c	the availability of a protected connection
A_s	the overall connection availability in a network

List of Abbreviations

APS: Automatic Protection Switching

BLSR/2: two-fiber Bidirectional Line-Switched Ring

BLSR/4: four-fiber Bidirectional Line-Switched Ring

DRWTA: Dynamic Routing, Wavelength and Timeslot Assignment

FWTA: Fiber, Wavelength and Timeslot Assignment

MILP: Mixed-Integer Linear Programming

MST: Mean Service Time

MTTF: Mean Time to Failure

MTTR: Mean Time to Repair

NP: Nondeterministic Polynomial time

OEO: Optical-Electrical-Optical

OTDM: Optical Time Division Multiplexing

PDH: Plesiochronous Digital Hierarchy

QoS: Quality of Service

RCL: Relative Capacity Loss

RWA: Routing and Wavelength Assignment

RWTA: Routing, Wavelength and Timeslot Assignment

SDH: Synchronous Digital Hierarchy

SHR: Self-Healing Ring

SONET: Synchronous Optical NETwork

TDM: Time Division Multiplexing

TTF: Time to Failure

TTR: Time to Repair

UPSR: Unidirectional Path-Switched Ring

VoD: Video-On-Demand

VoIP: Voice over IP

WDM: Wavelength Division Multiplexing

WTA: Wavelength and Timeslot Assignment

Ch. 1 Introduction

This thesis considers novel distributed traffic control schemes for dynamic flexible bandwidth on demand in next-generation all-optical metro networks, which are agile and intelligently managed to provide enormous capacity, flexible bandwidth and high quality of service at a low cost.

Traditional communication networks employed multi-layered structure to provide guaranteed services with high availability and security but at the expense of very high setup and operational costs. Being the only network services available at that time, the high revenue of these critical services made the networks affordable [Benj01]. This situation changed with the emergence of the Internet, a packet switching network developed in the 1970s. Today, the Internet connects millions of small computer networks using different kinds of media, such as copper wires, fiber-optic cables and wireless connections, and the best effort IP traffic carrying various information and services in the Internet becomes the dominant form in network service prospect. The rapid popularity of the Internet and the exponential growth of IP traffic come from some characteristics of the Internet: the diversified supporting network infrastructures, the low setup and operational costs, the standardized open system interconnection protocols, and the world wide connectivity of the Internet. As a result, the transformation of the legacy guaranteed services from traditional communication networks to the Internet has been a prominent topic for almost a decade. However, current Internet technology is not capable of providing appropriate Quality of Service (QoS) for these guaranteed services. In addition, as more and more end users go on-line, electronic business services tend to be a strong growing part in Internet traffic, which requires guaranteed continuity and security to ensure the success of these businesses. Moreover, with the even faster popularity of multimedia applications in recent years including IPTV, video-on-demand (VoD), video conference, voice over IP (VoIP), and other emerging applications that require short-lived high bandwidth connections, there is an ever-increasing need for fast, flexible and high-quality network services. Therefore, the next-generation communication networks should be designed to have integrated architectures with fewer physical layers to support high-growth IP traffic with flexible and differentiated QoS service requirements at reasonable costs.

In today's enterprise networks, Ethernet is still the primary option and is continuously making profit for its users because of its simplicity, prior-implemented advantage and wide applications [Rama06]. Driven by the exponential growth of data traffic in enterprise networks, a variety of optical interfaces are being made available for Ethernet, such as 100 Mbps, Gigabit, and 10 Gbps Ethernet cards. While still enjoying their revenue primarily on Synchronous Optical NETwork/Synchronous Digital Hierarchy (SONET/SDH), service provider networks tend to evolve to Ethernet because of the growing demands of Ethernet-based business services. With the popularity and improvement of optical interfaces in enterprise networks as well as the preliminary capacity and security requirements from service provider networks, optical networks are the favored transport platform for both enterprise and service provider Ethernet networks. However, to become a solid supporting layer in next-generation Ethernet-based communication network infrastructure, optical communication systems should migrate from slow and manual-operated networks with limited capacities to fast, smart-controlled and cost-effective networks with enormous capacities.

The capacity of optical networks has two aspects: optical fiber transmission systems and optical switches. A near-perfect optical fiber transmission system has low attenuation, very wide bandwidth, and immunity from most types of interference. Today, the increase of link speed in optical fiber transmission systems is impressive [Rama06]. An optical fiber can support a couple of hundred wavelengths using Wavelength Division Multiplexing (WDM) with each wavelength operating at the speed of up to 40 Gbps.

While experiencing the exciting progress in optical fiber transmission systems, the development of optical switches has not been as rapid. In traditional optical switches, all input optical signals are demultiplexed in the optical domain and converted into electrical signals by Optical-Electrical conversions. Then, the electrical signals are switched by an electrical switch module to the corresponding output ports. Finally, the electrical signals are converted back into optical signals by Electrical-Optical conversions and the resulting optical signals are multiplexed together on each output port in the optical domain and sent onto outgoing optical fibers. In short, traditional optical switches rely on electrical cores with fast memories and Optical-Electrical-Optical (OEO) conversions to process routing and control functions and to regenerate optical signals. Therefore, the switch scalability mainly depends on fast memory and OEO conversion technologies [Agil05]. However, not only are fast memories and OEOs the most expensive and power-consuming elements in optical switches, but they also limit the possibility to turn Gigabits or Terabits of optical fiber transmission bandwidth into completely usable optical network capacity [Pare05]. All-optical networks have thereby been proposed.

Whether a technology is successful (meaning commercial implementation and profit generation) or not, depends on if the technology reduces capital and operational costs or produces new revenue for its users [Rama06]. All-optical design eliminates OEOs from optical data paths and aims to push optical fibers closer to individual homes and businesses, which allows capital cost savings with the growth of network scales. This design also reduces ongoing operational costs by automating end-to-end service provisioning and management, inventory and resource tracking, and dynamic power management. In addition, all-optical switching is bit-rate and protocol transparent to upper layers and therefore facilitates future deployment of new technologies.

Having huge usable network capacities, the next question is how to efficiently utilize these bandwidths in all-optical networks to accommodate dynamic traffic with flexible bandwidth requirements. Wavelength Division Multiplexing (WDM) in fiber optical networks has been considered as an efficient data transport mechanism. However, as per-wavelength bit-rate moves up to 40 Gbps and beyond, WDM may lead to low channel utilization when certain applications or traffic flows do not need the full bandwidth of a wavelength. To address this issue, one approach is to apply Time Division Multiplexing (TDM) on wavelength channels to further divide each wavelength channel into sub-channels in the optical domain. The wavelength and timeslot routed WDM-TDM all-optical networks are thus formed [Srin02]. In this way, bandwidth virtualization is enabled where the bandwidth allocation for network traffic demands is decoupled from wavelength channels. The capacity of a wavelength can be shared by multiple small data flows. On the other hand, high bandwidth demands, such as 100G Ethernet, can be accommodated into the timeslots across several wavelength channels. Therefore, the WDM-TDM implementation enables the accommodation of data flows with flexible bandwidth requirements at an appropriate granularity, supporting a variety of date rates ranging from sub-wavelength to super-wavelength. The all-optical networks, which are intelligently controlled to serve multi-rate data flows, are referred to as *agile all-optical networks*.

Today, optical networks are increasingly being deployed in metropolitan areas [Rama06]. Metropolitan ("metro") networks differ from long-haul networks in that traffic carried in metro networks is highly changing and dramatically growing. Moreover, metro networks are characterized by rich and flexible services, cheap equipment and short distances. As it is advocated worldwide to bring fiber systems closer to network end users, it is believed here that more agile all-optical networks will be deployed in metropolitan areas.

One of the challenges involved in designing agile all-optical networks is the development of efficient algorithms and protocols for the control of dynamic traffic with flexible bandwidth requirements. This thesis focuses on the dynamic and flexible traffic control in agile all-optical metro networks and covers the following aspects of traffic control plane: bandwidth allocation, signaling and reservation, and network protection and restoration.

The first part of dynamic traffic control in this thesis investigates the bandwidth allocation in agile all-optical metro networks. The bandwidth allocation algorithms should be able to select routes, assign wavelengths and timeslots for lightpath connection requests with the objective of maximizing network resource utilization and minimizing connection blocking [Zang00]. The basic requirement for the accommodation of dynamic traffic in agile all-optical metro networks is time efficiency. Before going into detailed traffic control mechanisms, it is important to determine a network control structure that can provide competent services to network users in a timely manner. In literature, there are two kinds of network control schemes: centralized and distributed [Rama01]. In a centralized network structure, the central node in a network controls all the activities of the switches within the network. In a centralized-controlled network, connection operations, such as establishing, maintaining, restoring and removing connections, are handled by the central node through receiving connection operation requests from each switching node, calculating connection accommodation decisions, sending switching instructions for the setting up of each connection request to all corresponding switches, and maintaining the database of nodal and link states for the whole network. A network with this kind of structure is well organized to achieve a global optimization of network resource utilization, but suffers from the need for a large degree of coordination between its central node and switching nodes. Thereby, centrally controlled networks do not scale well to large sizes. In addition, centralized networks may experience performance degradation by the ineffective communication between the central node and switch nodes in each network, and a single central point failure will cause a whole network crash.

To keep good communications between nodes, some rules, referred to as protocols, should be defined to exchange information and maintain coordination between network nodes. With a distributed network structure, each node in a network has the intelligence to work competitively and cooperatively with other nodes in controlling the setting up and/or tearing down of connections within the network. This kind of structure is recognized to be better than a centralized scheme for dynamic traffic handling because of its robustness and better signaling performance, although it requires more network resources to achieve the same blocking performance as the centralized scheme [Rama01].

As the tendency is to push optical networks closer to end user sites and to accommodate more kinds of multimedia traffic, the distributed structure is preferable for the next-generation all-optical networks. However, the traditional distributed structure is not capable of managing the current ubiquitous and pervasive communication environment. In this thesis, the control of next-generation all-optical networks is divided into several levels with the idea of simplicity and efficiency. At the nodal level, each switch is centralized-controlled to become a basic network component, which has integrated functions that aim to achieve its local maximum and has the necessary nodal outage-prevention mechanism to improve component and system reliability. At the network level, the interconnected self-managed switches form a distributed-controlled network where information exchanges are localized, minimized, and only occur as needed in order to simplify network control and improve network efficiency. At the autonomic system level, the design of control protocols should be service-oriented aiming to fulfill various network service requirements with the ability of network evolving and self-optimization.

Having determined the control structure, dynamic traffic control can then be considered under this guideline. In a wavelength-routed WDM network, dynamic traffic accommodation is done by the operation of connections, referred to as lightpaths, which should be set up before network end users can communicate with each other. A lightpath is a WDM channel that carries traffic from one end user (the source) to another end user (the destination), which may span multiple fiber links and may use the bandwidth of one wavelength or several wavelengths. When there are no wavelength converters present in a WDM network, a lightpath must stay on the same wavelength(s) throughout all fiber links on the way from the source to the destination of a connection. This restriction comes from the property of optical networks known as the *wavelength-continuity constraint*. In a timeslot and wavelength-routed WDM-TDM network, the bandwidth of one wavelength is further divided into timeslots. Through incorporating agility and intelligence, a lightpath in a next-generation all-optical network has the flexibility of using the bandwidth of one timeslot or multiple timeslots on one wavelength, or the bandwidth of one wavelength or multiple wavelengths [Boch04]. Similar to the case of WDM networks, traffic follows the wavelength continuity constraint when no wavelength converter exists in a WDM-TDM network. In addition, when neither timeslot interchanger nor optical buffer is available, traffic on one lightpath does not change timeslot(s) on its way from the source to the destination. This limitation is known as the *slotting constraint*.

In wavelength-routed WDM networks, the problem of bandwidth allocation for connection requests is known as Routing and Wavelength Assignment (RWA) problem.

The traffic in optical networks can be modeled to be static or dynamic [Zang00]. A static traffic model is normally used in networks where the whole set of connection requests is known in advance. A dynamic traffic model is typically applied to networks where connection requests arrive one at a time and last in a finite time. For networks where traffic is well described by a static traffic model, the RWA problem becomes the problem of how to make the best usage of network resources for a given set of connection requests. The static routing and wavelength assignment problem is normally formulated to be an optimization problem and has NP-complete complexity [Zang00]. It can also be decoupled into a routing sub-problem and a wavelength assignment sub-problem to simplify the problem solution and then solve the two optimization sub-problems step by step. For networks where traffic is represented by a dynamic traffic model, the real time requirement requests the routing and wavelength assignment to be simple and fast. Therefore, the RWA problem is typically decomposed into a routing sub-problem and a wavelength assignment sub-problem at first. Then, depending on the networks' topology and the designers' objective, routing can be implemented with either static routing methods (fixed routing or fixed alternative routing) or adaptive routing methods. Next, with the routing decision from the previous step and the consideration of the timeliness requirement, heuristic approaches are commonly used in solving the wavelength assignment sub-problem for dynamic connection requests.

In timeslot and wavelength-routed WDM-TDM networks, the problem of bandwidth allocation is defined as a Routing, Wavelength and Timeslot Assignment (RWTA) problem. As the approach of optical domain time-division multiplexed wavelength channels has only recently emerged, the RWTA problem in WDM-TDM networks has not yet been well addressed in literature while some works have been done for traffic accommodation [Subr99], [WenS02], [YuWo02], [Chen04]; most of which consider single-rate traffic or utilize static traffic models. Aiming at metro networks, this thesis focuses on traffic patterns that are highly dynamic with flexible data rate. In this thesis, bandwidth allocation (RWTA) schemes for multi-rate dynamic traffic are analyzed in a practical perspective for agile all-optical networks, where neither wavelength converter nor optical buffer is available in order to decrease the expenses of metro networks. Here, the ring is designated to be the topology of next-generation metro optical networks because of its simplicity, survivability and cost effectiveness.

The second part of dynamic traffic control in this thesis studies the signaling and reservation of resources in agile all-optical metro networks. The signaling and reservation protocols are responsible for the exchange of network state information in order to manage network connections effectively [Rama00]. Signaling is the information exchange regarding the connection operation and the network management, which can be done in-band where signaling information is exchanged within the same channels that carry user traffic, or out-of-band where a separate channel is dedicated for signaling purposes. In wavelength-routed WDM networks, signaling controls network switches to set up, maintain, restore and remove lightpaths. When network traffic control is based on global information, signaling is also responsible for network state information updates.

Reservation is a process to reserve network resources for the setup of lightpaths. Reservation may be categorized as parallel reservation, forward hop-by-hop reservation and backward hop-by-hop reservation [Zang00]. In parallel reservation, the source node of each lightpath request sends separate control messages – reservation requests to each node on the route of the lightpath to have each node on the route reserve corresponding resources on its link. In a hop-by-hop manner, only one reservation control message is sent by the source node for each lightpath request. Network resources are either reserved while the control message is passing to the destination node of a lightpath request (forward reservation), or reserved while an acknowledgement message toward the source node is sent back from the destination node after it receives the control message of the reservation request from the source node (backward reservation).

In some cases, signaling and reservation protocols have to be directly integrated with routing, wavelength and timeslot assignment algorithms, which depend on whether global network state information is utilized by the signaling and restoration protocols and how much network state information is available while incorporating a distributed mechanism [Zang00]. In this thesis, signaling and reservation protocols are investigated based on the characteristics of metro networks with the studying of global information updating protocol and the performance gain of global information exchange. In a network where state information is exchanged between network nodes, there exists a time delay to have global information be convergent on all network nodes whenever the network state changes. Hence, when dynamic traffic is highly variable in time, it is possible that out-dated global information is utilized during the bandwidth allocation stage. This, in turn, may result in unsuccessful lightpath setups. On the other hand, in a network where only local information is available on network nodes, the network propagation delay may not be ignorable compared with the time scale of highly variable dynamic traffic. This may also result in out-of-date state information during the signaling and reservation stage and may thereby cause unsuccessful lightpath setups. Dynamic traffic control protocols are therefore evaluated on their blocking performance degradation in the presence of the stale state information.

The third part of dynamic traffic control in this thesis addresses the survivability of agile all-optical metro networks. Network protection and restoration functionality, realized through connection protection and restoration, is one of the essential requirements for networks [Gers00a]. It is even more critical in next-generation optical networks with huge capacities, in that a small time of outage will cause a large amount of user traffic loss. Network survivability is the ability of a network to maintain the continuity of critical services to end users in the presence of network failures [Gers00b]. It can be implemented in many layers and most layers operating above the optical layer have full protection functions on their own. However, optical layer protection and restoration still plays an important role in network survivability because of its speed, cost effectiveness, and the efficiency in dealing with certain types of failures. This thesis addresses the survivability of agile all-optical metro networks in a service perspective focusing on dynamic and flexible traffic. The possible multiple-layer cooperative survivability schemes will also be discussed in the face of service-driven autonomic system.

The main objective of this thesis is to investigate the dynamic and flexible traffic control in next-generation all-optical metro networks. For this purpose, this thesis will cover the following aspects of traffic control plane: bandwidth allocation, signaling and reservation, and network protection and restoration. Detailed steps are listed as follows.

- Define the architecture of next-generation all-optical metro networks, on which the following research of dynamic and flexible traffic control is based. Set up network model and traffic model for this thesis.
- Starting from single-fiber networks, propose a bandwidth allocation scheme based on the study of the bandwidth allocation schemes in WDM networks and evaluate its performance through a simulation model.
- Develop a mathematical model for blocking analysis in single-fiber networks and verify it through simulation.
- Generalizing to multi-fiber networks, study the bandwidth allocation schemes and utilize simulation models to compare their performances.
- Develop two control protocols with the awareness of global network state information for signaling and reservation, and compare the performances, costs and efficiencies of the two protocols.
- Develop a control protocol with only local network state information for signaling and reservation; study its performances and costs; and compare it with the two signaling and reservation protocols with global network state awareness.
- Investigate optical survivability and propose channel-based protection in agile all-optical metro ring networks.
- Applying the channel-based protection in single-duct agile all-optical ring networks, present a rearrangement scheme to decrease network blocking.
- Develop a proactive span switching and reactive ring switching mechanism for the protection of dual-duct agile all-optical rings.

This thesis is organized as follows: **Chapter 2** lists several background achievements from other researchers related to the work presented here, covering the main areas to build next-generation all-optical networks. **Chapter 3** describes the architecture of the agile all-optical metro networks used here, on which the research of dynamic and flexible traffic control in the following chapters is based. Then, the network model and traffic model are outlined. **Chapter 4** begins with a distributed dynamic routing, wavelength and timeslot assignment algorithm for bandwidth on demand in single-fiber metro ring networks. To simplify the blocking analysis in single-fiber metro ring networks, a quasi-analytical blocking model is thereafter proposed. With the generalization of blocking study from single-fiber metro ring networks to multi-fiber metro ring networks, a systematic comparison has been made for heuristic approaches combined with a fiber designation scheme in bandwidth allocation for dynamic connection requests. **Chapter 5** studies the signaling and reservation schemes for dynamic and flexible bandwidth requests by comparing two kinds of control protocols with or without global network state information and examining their impacts on network blocking. **Chapter 6** introduces and describes some issues of optical survivability for next-generation all-optical metro ring networks. **Chapter 7** concludes this thesis.

Ch. 2 Background

This chapter presents some achievements from other researchers related to the work in this thesis, covering the main areas to build next-generation all-optical networks.

2.1 Agile all-optical networks

Recent advances in optical networks have realized a couple of hundred WDM wavelength channels per fiber and 40 Gbps per wavelength [Rama06]. Compared with this significant link rate increase, the increase of packet processing rate is relatively small, which results in the limitation of optical network capacity. Traditionally, data packets traversing an optical network usually undertake multiple fast memories and Optical-Electrical-Optical (OEO) conversions in order to be routed and controlled. However, fast memory and OEO conversion are expensive and consume a great deal of power. Therefore, the architecture of optical networks, where data traffic experiences OEO conversions, has limited scalability.

All-optical networks have been proposed to perform both data transmission and switching in the optical domain [Agil05]. By eliminating the bottleneck of OEO conversions from data paths, the proposed solution extensively accelerates the speed of data transmission and switching, while greatly decreasing the network equipment costs. Apart from the significant network capacity increase, keeping data traffic in optical domain enables lightpaths to be transparent to both data format and bit rate, which facilitates network evolution and reach. The main disadvantage of all-optical networks is the difficulty in implementing packet switching in the optical domain because of the deficiency of optical buffer and the absence of methods in dealing with addressing or labeling.

Newly emerging agile all-optical networks have been proposed to provide enormous capacity, flexible bandwidth and high quality of service at a low cost [Agil05] [Boch04]. Currently, Wavelength Division Multiplexing (WDM) has been widely deployed as an efficient data transport mechanism for all-optical networks. However, as per-wavelength speed moves to 40 Gbps and beyond, certain applications or traffic flows do not need the full bandwidth of a single wavelength. For this reason, current wavelength-routed WDM technique may lead to low channel utilization and thus low network utilization. To address this issue, one approach in agile all-optical networks is to further divide a wavelength channel into sub-channels by incorporating time-division multiplexing (TDM) on each wavelength channel in all-optical network [Boch04][Agil05]. In this way, several data flows with less bandwidth requirements may share the capacity of a single wavelength. Moreover, flexible bandwidth, where data flows are able to have different data rates, is supported by the implementation of TDM over WDM channels. The appropriate bandwidth granularity can be achieved by the careful design of the size of a timeslot in the two dimensional WDM-TDM multiplexing scheme. With the integration of agility and intelligent control, all-optical switching is capable of accommodating highly dynamic traffic requests with flexible bandwidth requirements. The primary challenge in putting the WDM-TDM multiplexing technique into practice is that optical switches must be well configured before the arrival of data flows to be switched while the switching requests for the transmission of these data flows come from multiple sources. The solution needs to be developed.

2.2 Routing algorithms

In wavelength-routed WDM networks, the Routing and Wavelength Assignment (RWA) problem can be solved statically or dynamically [Zang00]. The static RWA problem with wavelength-continuity constraint is typically modeled in the form of the mixed-integer linear programming (MILP) problem. The objective of this kind of MILP problem can be minimizing the number of wavelengths required for a given set of connection requests, or maximizing the number of connections that can be set up for a fixed number of wavelengths and a given set of connection requests [Rama95], [Bane96], [Zang00]. Since the complexity of the MILP problem is NP-complete (NP: Nondeterministic Polynomial time) [Zang00], the optimization procedure involved in the solution of the static RWA problem is computational intensive. Thus, solving the RWA problem statically is only applicable for the accommodation of traffic patterns that stay in a network for a long period of time.

To simplify the solution, the RWA problem can be decoupled into two separate subproblems: the routing subproblem and the wavelength assignment subproblem [Gers97]. It has been shown in [Carp02] that the performances of some two-phased heuristic approaches are very close to the results derived from the MILP optimized solutions over a range of problem types for the static routing and slot assignment on ring networks. In addition, the decomposition of the RWA problem also makes it possible for dynamic lightpath accommodation [Zang00]. In this section, various network routing approaches will be introduced.

The routing subproblem can be solved statically or adaptively using either global network state information or local state information [Zang00]. In static routing, route selection is time invariant while in adaptive routing, routing algorithms utilize network state information in route calculation at the time of connection establishment. Two commonly used static routing algorithms are fixed routing [Birm95] and fixed alternative path routing [Hara97] [Rama98]. Fixed routing algorithm always routes connection requests to a predetermined route for each source-destination pair. One common example of fixed routing approaches, fixed shortest path routing, routes traffic along a route calculated off-line using a standard shortest path algorithm (Dijkstra algorithm or Bellman-Ford algorithm) for each source-destination pair. Fixed routing algorithm is simple. However, it has two main disadvantages [Zang00]. One is that fixed routing does not base routing decisions on the loads of network links. Consequently, it may lead to inefficient network link utilization, which may cause high blocking probability in dynamic case, or result in a large number of wavelengths being required or a small number of connections to be established in static case. The other disadvantage of fixed routing is that a pre-determined route does not work when network links it passes encounter a failure or failures.

By defining multiple routes, fixed alternative path routing algorithm aims to solve the above two problems while keeping some extent of simplicity, which is the main advantage of fixed routing [Zang00]. In fixed alternative path routing, multiple routes are pre-determined for each source-destination pair and saved in order in the routing table of each source node. Fixed alternative path routing algorithm selects the first available route in the routing table for each connection request. Since the primary route and alternative routes are link-disjoint, the fixed alternative routing algorithm has some degree of fault tolerance for link failures. Previous researchers' works have also shown that this algorithm significantly cuts down the rate of connection request blocking comparing to fixed routing algorithm [Hara97], [Rama98].

Adaptive routing chooses routes for connection requests depending on network state, which is defined as the set of all connections existing in a network [Zang00], [Mokh98]. As adaptive routing adjusts to network state, connections can always be set up except there is no route from a source node to a destination node in a network. The algorithm has lower blocking probability than static routing. However, adaptive routing requires extensive support from network control and management protocols to continuously update network state, and can lead to computational complexity [Zang00]. The approaches in adaptive routing can be categorized as global information based adaptive routing, which can achieve lowest blocking, and neighborhood information based adaptive routing, which simplifies the algorithm by using only neighborhood information in route decision making.

2.3 Wavelength and Timeslot assignment methods

Considerable work has been done in the area of finding efficient algorithms for the wavelength assignment subproblem [Rama95], [Zang00]. The approaches depend on whether it is a static wavelength assignment or a dynamic wavelength assignment. For static cases, the problem becomes assigning a wavelength to each lightpath for a given set of lightpath requests and their routes in such a way that no lightpaths share a same wavelength on any fiber. One typical solution to the problem is to transform the problem into a graph coloring problem trying to minimize the number of colors needed to color a graph, which has been shown to be NP-complete [Zang00]. Many heuristics and bounds have been developed in literature for this NP-complete problem.

For dynamic cases, traffic in a network can be modeled using a traffic matrix, which changes over time to express the arrivals and departures of lightpath requests in the network [Chen03]. This model assumes traffic requirements to be stable for a period of time and is good for the modeling of traffic patterns that change in weeks or months. Thus, the model is also called semi-dynamic model. For network traffic that can be represented by semi-dynamic model, wavelength assignment aims to accommodate any traffic matrix with or without network reconfiguration and/or lightpath request rearrangement. For a given traffic set in a traffic matrix, the solutions are focused on finding the no-blocking boundaries such as the minimum number of wavelength converters, or the maximum number of ports for each node, or the minimum number of wavelengths used as well as the bound of maximum load on each link, etc. Some heuristics have been proposed in literature for solving the wavelength assignment problem with this traffic model, e.g., MAX-SUM [Subr97] and Relative Capacity Loss (RCL) [Zhan98].

An alternative model of dynamic traffic is that lightpath requests arrive or depart one at a time following some statistic distributions [Zang00]. This model is good for the modeling of highly dynamic traffic. Approaches with this model are focused on minimizing blocking probability for a given network. Due to the complexity of the problem, many heuristic wavelength assignment schemes have been proposed in the literature such as Random Wavelength Assignment, First-Fit, Least-Used, Most-Used, Least-Loaded, etc.

1. Random (R): Random wavelength assignment method searches the whole wavelength space to find all available wavelengths on a given route and randomly picks one wavelength among all available wavelengths. The algorithm distributes dynamic traffic randomly so that the average fiber/wavelength utilizations are balanced. No global information is required for the scheme.
2. First-Fit (FF): In this scheme, all wavelengths are numbered. The algorithm chooses the available wavelength with the lowest number. FF aims to pack wavelengths in use in a fixed order towards the lower end of wavelength space and leave more idle wavelengths at the higher end of wavelength space for longer hop count lightpath requests in order to reduce the blocking probability. Therefore, FF has better blocking

performance than R. Compared with the Random algorithm, this scheme needs less computation because it does not need to search the whole wavelength space for all available wavelengths for each route. Similar to R, FF does not require global information and is preferred in practice for its blocking performance, simplicity and fairness.

3. Least-Used (LU): This scheme selects the least used wavelength in the network. LU is a spread algorithm trying to distribute dynamic traffic among all wavelengths. LU performs worse than R and needs global information to compute the least-used wavelengths. It is not preferred in practice.
4. Most-Used (MU): MU takes the wavelength that is used most often in the network. The algorithm packs connections into fewer wavelengths so that network links have more idle wavelengths in common to accommodate longer hop lightpath requests. The blocking probability of MU is slightly better that that of FF. This scheme requires global information to compute the most used wavelengths.
5. Least-Loaded (LL): LL is a most common heuristic approach designed for multi-fiber networks. It selects the wavelength that has the largest idle capacity on the link that is most heavily loaded along each route. LL becomes FF for single-fiber networks. In terms of blocking probability, LL outperforms FF in multi-fiber networks. The scheme does not require global information and thereby is preferred in practice to be deployed in multi-fiber networks for its blocking performance and simplicity.

Compared with a variety of wavelength assignment approaches in the literature, timeslot assignment schemes have limited addressing. The works in literature investigating different aspects of timeslot assignment are introduced briefly as follows: The wavelength and timeslot assignment problem is studied for a given set of multi-rate sessions in bus and ring topology in [Subr99] in order to maximize network throughput. This early work was the first to provide bounds to the multi-rate session scheduling problem. Nevertheless, it considers a static traffic model based on the traffic requirements for optical networks at that time where the duration of lightpaths are of the order of months. This approach is no longer appropriate to model the traffic arising from newly emerging network applications that are going to be carried in next-generation networks, where traffic is highly changing in time. Conversely, the dynamic traffic model is used for the assignment problem in [WenS02]. Three variations of LL timeslot assignment scheme combined with a LL wavelength assignment scheme are presented and compared for mesh networks without either wavelength converter or optical buffer. However, this work has not discussed the impact of the characteristic of multi-rate traffic on the feasibility of these wavelength and timeslots assignment approaches. In addition to the above works considering optical networks without wavelength converter and optical buffer, [YuWo02] and [Chen04] investigate the timeslot assignment problem for optical networks having a small amount of optical buffer. Three heuristic approaches for routing and timeslot assignment are presented in [YuWo02] with the goal of reducing blocking probability or decreasing buffer requirements. The research in [Chen04] focuses on the routing and timeslot assignment schemes in networks with a small buffer size, aiming to maximize the buffer efficiency. Although wavelength converter and optical buffer have been developed for optical networks, they are still very expensive as of the state-of-art technology. Therefore, in this thesis, it is reasonable to assume that both wavelength converter and optical buffer will not be widely implemented into live all-optical metro networks in the near future.

2.4 Blocking Analysis

In circuit switched networks where connection requests arrive randomly and are served by assigning some network resources for the durations of the requests, call blocking probability is a common metric of performance. In fact, the feature that voice connections are of the order of minutes makes call blocking probability a very important metric in telephony networks. Similarly, call blocking probability is recognized as a rational metric for traditional optical networks, although the durations of dynamic lightpaths are at the order of weeks or months, which are considered very large time scales [Srid04]. Furthermore, next-generation all-optical networks are driven by newly emerging multimedia broadband dynamic traffic demands. The connection requests of these services are of the order of minutes or hours. Combining this feature of network services with the huge bandwidths of network channels, it is believed here that call blocking probability will play a more critical role in evaluating the performance of agile all-optical networks.

Call blocking probability analysis is an essential step in the design of networks to accommodate dynamic traffic. In literature, there are two methods to analyze call blocking probability: conducting network blocking simulations or building an analytical model for network blocking. A simulation is the imitation of the processes in systems in the real-world [Bank00]. It is one of the most widely used and accepted tools in the field of research. Simulations can appropriately be used to verify new designs or policies before implementation. They are also useful in the verification of analytic solutions. Nevertheless, to realize a valid simulation, a great deal of thought must be done in problem formulation, model verification and validation, simulation runs, and output analysis, etc. Therefore, it is not recommended to use simulations if a problem can be solved in an analytical way. On the other hand, analytical models are hard to achieve for sophisticated systems. In most cases, some assumptions have to be made, which may impact the accuracy of the analytical models. However, an analytical solution is preferable if a model with appropriate accuracy can be found for a problem because solving a problem with an analytical method can be much faster and more economic than solving it with simulations.

Many researchers have studied call blocking probabilities for circuit-switched WDM networks with or without wavelength changers, such as in [Barr96], [Birm96] and [Srid04]. In [Barr96], Barry makes a simplistic traffic assumption and proposes a model to study the effects of wavelength converters, path lengths, nodal degrees and interference lengths for an arbitrary network topology. The model also considers load correlation between links introduced by the wavelength continuity constraint. However, the dynamic feature of traffic has not been included in the model. Another model proposed by Birman [Birm96] studies two types of small networks, arbitrary or full mesh, where connections are up to 2 or 3 hops separately. Fixed routing, least loaded routing and fixed alternative routing are investigated for dynamic traffic with state-dependant arrival rate. The accuracy of this model is shown to be good for the fixed routing case.

However, the model is only valid for small networks because the complexity of the model grows exponentially with the increase of number of hops. In addition, the model does not consider the load correlation introduced by the wavelength continuity constraint. Thereafter, Sridharan [Srid04] proposes an independent model and a correlation model based on the two previous works with lower computational complexity and dynamic traffic considerations. It utilizes the birth-death process to model the state of wavelength occupation on a link. Compared with the independent model, the correlation model where load correlation introduced by wavelength continuity is considered results in better accuracy.

For the circuit-switched WDM-TDM optical networks, some models have been proposed, [Yate99] and [Zhou04] providing two examples. In [Yate99], Yates proposes a model to analyze the performance gain of wavelength converter and timeslot interchanger for dynamic traffic in multi-wavelength TDM networks with random wavelength and timeslot assignment. This is the first work in the field to our knowledge. However, it deals with single-rate traffic models and investigates blocking performance for traffic with a fixed number of hops. In [Zhou04], Zhou proposes a model to study the blocking performance for arbitrary network topologies and traffic patterns in Optical Time Division Multiplexing (OTDM) networks. The model can also be applied to networks with multiple fibers or networks with wavelength converters. With relatively low complexity, the model achieves good accuracy. Aiming at traffic patterns with one timeslot bandwidth requirement, the work uses the birth-death process to model the state of timeslot occupation on a wavelength of a link, which cannot be extended to networks with traffic patterns of flexible bandwidth requirements.

2.5 Signaling and reservation

Signaling and reservation protocols are used to exchange control information and to reserve resources along the routing path when establishing network connections for dynamic requests [Zang00]. For dynamic traffic control, signaling and reservation protocols should be able to effectively manage control messages and network state information in order to perform network connection operation in a timely manner.

Signaling and reservation protocols can be categorized by whether the knowledge of network state information, noted as global information, is available or not in the process of signaling and reservation [Zang01].

2.5.1 Signaling and reservation with global information

When global information is available, the routing and wavelength assignment problem is solved before signaling. Signaling and reservation can then be implemented in either a parallel basis or in a hop-by-hop manner. Parallel signaling and reservation achieves shorter connection setup time, but it also significantly increases the amount of network control traffic. In the parallel configuration, the source node of each connection demand sends a separate connection reservation request to each node on the routing path and requires an acknowledgement from each node on the routing path to indicate whether the reservation process on each node along the path is successful. While using the hop-by-hop scheme, the source node of each connection demand sends only one link reservation request along the routing path to the destination node. Upon receiving the control message, each intermediate node on the path processes the message and then forwards the message to the next hop. While receiving the control message, the destination node sends either a positive or negative acknowledgement back towards the source node along the routing path to signify the reservation result after the processing of the reservation request. In the hop-by-hop scheme, the link resource reservation can be performed while the reservation request is transmitted from the source node to the destination node (Forward Reservation) or when the acknowledgement is traveling backwards (Backward Reservation). The Forward Reservation scheme is faster than the Backward Reservation scheme in that any intermediate node can terminate the signaling and reservation process by replying with a negative acknowledgement to the source node of a connection demand when it finds insufficient resources in its links requested by the reservation request.

In a signaling and reservation process, global information can either be collected by one central controller or be exchanged among all network nodes obeying some rules. Compared with centralized control schemes in global information collection, distributed control approaches have a higher degree of coordination among network nodes, but avoid the problem of the fatal single point of failure. In order to decrease the amount of control traffic in the distributed global information exchange in optical networks, the content of global information is proposed to be classified into two kinds: quasi-static information and dynamic information [LiYa02]. Quasi-static information includes neighbor relationship, total link bandwidth and optical impairment parameters of each link, which does not change with connection status in a network at any time [Shen06], [LiYa02]. Dynamic information only includes link-state information, which is represented by wavelength and timeslot availability at each link that changes in response to dynamic connection status. Quasi-static information can be manually provisioned into the network configuration or refreshed via infrequent advertisements. Dynamic information need to be updated frequently to reflect dynamic connection operations.

As link-state information changes whenever there is a connection established or removed, broadcasting each real time change of link-state information will result in significant control message overhead and an unstable link-state database when a network serves high-arrival-rate short-lived traffic patterns. To avoid this situation, two approaches have been proposed for distributed link-state information exchange in a network in order to renew the global information database in each network node [Shai01]. One is the periodic update approach, where link-state updates are propagated for every fixed interval of time – update period. The other is the triggered update approach, where link-state updates are advertised when the amount of state changes in a network reaches certain predetermined thresholds. In either case, some link-state information may be out-of-date during the time between two adjacent state updates. The outdated link-state information in turn may lead to incorrect routing and wavelength assignment decision and may therefore cause blocking or loss.

In networks applying the periodic update approach for global information exchange, shown in [Shen04a], blocking probabilities are sensitive to the length of update period, especially when networks are in the conditions of light traffic loads. Long update periods cause high blocking probabilities. When a triggered update approach is deployed for global information exchange, network blocking performance is sensitive to the changes in trigger parameters, which includes the trigger threshold, the hold-down timer and the regular update timer [Shai01], [Shen04b]. The hold-down timer, which is imposed to avoid overloading the network bandwidth and processing resources during rapid fluctuations in link bandwidth, defines the minimum time between two adjacent update messages. A regular update timer determines the maximum time between any two update messages, which forces the advertising of the updates of link-state information when the trigger threshold is hard to reach during infrequent transitions in link bandwidth. Similar to the case of the periodic update approach, large timers and coarse trigger thresholds result in significant degradation of blocking performance [Shai01], [Shen04b]. Moreover, it is noted that there is no significant difference in overall blocking performance between the approaches of periodic link-state update and triggered link-state update [Shai01], [Shen04b].

2.5.2 Signaling and reservation without global information

When global information is not available, signaling and reservation should be integrated with Routing and Wavelength Assignment (RWA) algorithms in order to set up a lightpath [Zang00]. In this case, reservation can be implemented in a forward or backward manner. The forward approach is an aggressive reservation scheme, which reserves all available wavelengths on links along the routing path when a signaling message travels from the source node to the destination node of a connection demand. Unnecessary wavelengths are released when the destination node selects one wavelength for the connection demand and a signaling message travels back from the destination node to the source node. This approach maximizes the probability of connection setup upon the arrival of a connection request, but may cause the blocking of following connection requests as extra resources are reserved for a short period of time.

To avoid resource overbooking, a backward reservation approach is proposed in the literature. This approach chooses an available wavelength for a connection demand when the signaling message of the connection demand arrives at the destination node, and reserves the wavelength while the signaling message goes back from the destination node to the source node [Zang00]. This approach has a significant weakness: concurrent connection demands may choose the same wavelength on a common link of their routing paths when signaling messages of these demands reach their destination nodes. In this case, only one connection can be set up and blocking occurs for other connection demands.

2.6 Optical layer survivability

Survivability, the ability of a network to maintain the continuity of critical services to end users in the presence of network failures, is one of the essential requirements of networks [Gerst00]. It gains more attention in fiber optical networks where network throughputs are at the order of gigabits or terabits per second, meaning that a single link failure has the potential to lead to the loss of a large amount of data and/or connections. Optical layer survivability plays an important role in the area of network survivability mainly because optical layer protection may be more efficient in handling some types of network faults. Furthermore, some client layers of the optical layer are not fully survivable from network failures.

The basic types of network failures generally considered in optical layer protection are channel failure, link failure and node failure [Zhou00]. A channel failure is usually due to the failure of a laser or detector on the channel; a node failure normally occurs when some parts of a network node fail; and a link failure is typically caused by fiber cuts. Various schemes have been proposed to handle node or link failures and little attention has been paid to protect against channel faults.

From the perspective of network infrastructure, survivability techniques can be classified into three categories: network element design, network design, and traffic management [Niko97], [Kesh04]. Network element design approaches focus primarily on improving component and system reliability by means of highly effective redundancy. Network design techniques mainly aim to alleviate the effects of system level failures by placing sufficient diversity and capacity in network topology. Trying to minimize failure impact on network loads, traffic management schemes are procedures to redirect network traffic when failures occur so that failure affected network loads can be properly transmitted around failures throughout networks.

From a service perspective, the approaches of network survivability can be classified as proactive protection and reactive restoration [Gerst03][Kart02]. In proactive protection, recovery from network failures is based on preplanned schemes. At the stage of network element and network design and/or at the time of connection setup, some resources are reserved for network failure recovery and kept idle when no failure occurs. This kind of approaches guarantees the level and speed of failure recovery, while suffering from inefficient resource utilization. The reactive restoration schemes seek to discover spare resources dynamically in networks to restore the affected network services when failures occur. Though more efficient in network capacity utilization than the proactive protection approaches, this kind of approaches may lead to an intolerably long service restoration time. Additionally, it cannot guarantee the level of fault recovery. These intrinsic drawbacks of the reactive restoration schemes disagree with the main objective of survivability. Thus, proactive protection is primarily adopted for optical layer survivability, and extensive research has been done on the benefits of the approach.

The most common proactive protection approaches are as follows:

1. Automatic Protection Switching (APS): APS is the capability to detect a failure on a working facility and to switch to a standby facility for transmitting or receiving. It has three main forms: 1+1, 1:1, 1:N and is generally used to handle link failure.
2. Self-Healing Ring (SHR): The main idea of SHR is to reroute traffic to the other part of a ring on the detection of a failure. SHR can protect from both link and node failure and is therefore more flexible than APS.
3. Link-based protection: This approach reserves a protection path for each link. When a link failure occurs, traffic is rerouted to the protection path of the link. In dedicated link protection, a protection wavelength path is assigned to a working lightpath on a particular link. On the contrary, in shared link protection, different protection paths can share the same wavelength on links in common along their routes if the corresponding working paths are link-disjoint.
4. Path-based protection: The idea behind this approach is to reserve a protection lightpath for each working lightpath. On the failure of a link or a connecting node, traffic is rerouted to the protection lightpath. Similar to link-based protection,

dedicated path protection reserves a backup lightpath for each working lightpath. This protection scheme is capable of recovering from multiple failures, but needs a large amount of extra capacity for protection purposes. Shared path protection allows the use of the same wavelength on a link for two backup lightpaths in case that the two primary lightpaths are on different links. It is designed to achieve more efficient capacity usage while guaranteeing 100% single failure recovery.

Currently, shared protection schemes have not been frequently deployed, as they may require more expensive equipment and more complex operations than dedicated protection schemes [Rama06]. In addition, the achievable protection switching time may not be within the 50 ms range.

Overall, network survivability mainly focuses on the case of one failure at a time, and assumes that the probability of two or more concurrent failures is relatively small and thus negligible. However, as the dimension of optical networks keeps growing and as the throughput of a single fiber increases dramatically, the probability of a simultaneous occurrence of multiple faults increases. In addition to addressing the single-failure problem by survivability, some researches turn to the study of the multiple-failure problem. This concept is distinguished from survivability and is named as disaster avoidance [Kart02]. The investigation of surviving a disaster considers large networks such as multiple rings or mesh networks.

2.7 Survivability measures

In optical networks, survivability is an essential requirement. Various approaches have been proposed in this area. A comparison of the proposed network architectures and corresponding survivability approaches is of interest for both researchers and network operators, whereby a survivability measure is required to give a quantitative idea regarding the performance of these approaches. Survivability measures are usually classified into three main categories: probability-based measures, topological measures and time measures [Mika04].

In the category of probability-based measures, availability is a primary measure that is related to the telecommunication system and networks, and defined as the probability that a given network element is working [Mika04]. Network availability is defined as the ability of a network to maintain a certain level of performance in the occurrence of network failures [Huan07]. Topological measures refer to some deterministic indications that usually depend on network topologies to estimate the ability of networks to survive failures, such as the number of available paths between a pair of nodes, etc [Kesh04]. The last category of measures, time measures, is related to the response timers that quantitatively characterize the ability of networks to restore disrupted services from different types of failures [Mika04].

While investigating networks with dynamic traffic model, availability is one of the most important measures in network survivability design. Most availability models focus on the analysis of steady-state availability where a network entity has a constant failure rate λ and repair rate μ [Mika04]. In this case, random variables of time to failure (TTF) and time to repair (TTR) have the exponential distribution. If mean time to failure (MTTF) and mean time to repair (MTTR) are defined as the means of the two random variables TTF and TTR, then $\lambda = 1/MTTF$ and $\mu = 1/MTTR$. The availability A of the network entity can be expressed as [Zhou07]

$$A = \frac{MTTF}{MTTF + MTTR} = \frac{\mu}{\mu + \lambda}$$

Suppose a system A_s consists of n independent and serially connected elements that have equal availability of A_i, then the availability of the system A_s is

$$A_s = \prod_{i=1}^{n} A_i \approx 1 - \sum_{i=1}^{n} U_i$$

where U_i is the unavailability of each element and $U_i = 1 - A_i, i = 1, ..., n$. The unavailability of the serial system is then

$$U_s \approx \sum_{i=1}^{n} U_i$$

The above equation holds while $U_s \ll 1$.

2.8 SONET/SDH vs. next-generation all-optical networks

Synchronous optical networking (SONET) and Synchronous Digital Hierarchy (SDH) are two closely related transmission and multiplexing standards for high-speed signal transportation over optical fibers [Rama02]. Different from traditional plesiochronous digital hierarchy (PDH), which utilizes asynchronous multiplexing, SONET and SDH adopt synchronous multiplexing structure to simplify multiplexing and demultiplexing significantly without bit stuffing. The entire inter-country networks of SONET/SDH are synchronized by atomic clocks so that the amount of buffering required between elements in networks is greatly reduced. SONET and SDH are based on circuit switching technology where each connection achieves a constant bit rate and delay, and are characterized with time division multiplexing (TDM) protocols. In current SDH/SONET multi layer networks, SDH/SONET connections are groomed to be a client layer to wavelength channels and transported over end-to-end lightpaths. This kind of solution realizes the bandwidth utilization efficiency of wavelength channels and makes dynamic bandwidth adaptation possible, which is one of the main reasons for the existence of SONET/SDH networks today. Next-generation all-optical networks aim to eliminate the SONET/SDH network layer from network infrastructure, and to implement wavelength channel efficiency and dynamic bandwidth allocation in the optical domain in order to significantly reduce capital and operational costs of networks, and to speed up network configuration, operation, maintenance and protection processes [Boch04].

A major achievement of SONET/SDH networks is the implementation of an extensive set of protection techniques and corresponding network management protocols that greatly improve network availability and reliability [Rama02]. Fundamentally, there are two types of protection schemes in SONET/SDH: 1+1 protection and 1:1 or 1:N protection. In 1+1 protection, traffic is transmitted simultaneously on two disjoint routes from source node and destination node. At the receiving end, signals carrying traffic from the two routes are compared by the destination node. The one that has better quality is chosen. When a network fault occurs, protection is simply switching data received to the route with the better signal quality at the destination node. Therefore, this kind of protection is quite fast without the need for any signaling protocol to support the protection process. In

1:1 protection, there are still two routes from source node to destination node. However, traffic is only transmitted over one route, named as the primary route, and does not take the other route, named as the backup route. When a network failure occurs on the primary route, the protection process invokes signaling protocol to implement fault detection, localization, and protection switching to switch traffic on to the backup route. This kind of protection introduces communication overhead in fault recovery. Thus, it is slower than 1+1 protection, but has two main advantages over 1+1 protection. First of all, the unused backup route can carry low priority traffic while no fault occurs. Secondly, 1:1 protection can be extended to 1:N protection where 1 backup route is used to protect N disjoint primary routes.

In SONET/SDH networks, protection techniques can be categorized as point-to-point link protection, unidirectional path-switched ring (UPSR), four-fiber bidirectional line-switched ring (BLSR/4) and two-fiber bidirectional line-switched ring (BLSR/2), etc [Rama02]. In point-to-point link protection, each link between two nodes is protected with 1+1 link protection, 1:1 link protection or 1:N link protection. In UPSR, one of the two fibers is defined as the working fiber and the other as the protection fiber. For each traffic flow, two paths are set up with one path in each fiber. Consequently, the traffic flow is transmitted clockwise on the working fiber and simultaneously carried counterclockwise on the protection fiber. UPSR is basically 1+1 protection technique implemented at the path layer of SONET/SDH network structure. In BLSR/4, two fibers are defined as working fibers and the other two are used for protection purpose. The protection switching in BLSR/4 includes both span switching and ring switching. Span switching occurs when a transmitter or a receiver fails on a working fiber. In this case, traffic is switched onto the protection fiber on the same links between two nodes. Ring switching happens on fiber cuts where traffic is routed onto the protection fiber on links on the other side of the ring. BLSR/2 is the cost effective version of BLSR/4, and is usually deployed in metro areas. In BLSR/2, only two fibers are used where each fiber provides half of its capacity to carry working traffic and reserves the other half of its capacity for protection. BLSR/4 and BLSR/2 are essentially 1:1 protection technique applied at the line/section layer of SONET/SDH network structure.

The protection techniques in SONET/SDH networks have been conceptually well applied into WDM networks [Rama02] and may also be used as references in the design of next-generation all-optical networks.

Ch. 3 Network Architecture

This chapter presents the architecture of the agile all-optical metro networks under the design here by describing the assumptions, node model, network topology, and network control, on which the research of dynamic and flexible traffic control in the following chapters is based. Then, the network model and traffic model is outlined for the following research. The basic assumptions are discussed in Section 3.1. The node architecture, network control and network topology considered in this thesis are given in Section 3.2. Section 3.3 builds the network model and the traffic model for the research in the following chapters. In this thesis, all the designed algorithms and protocols for dynamic and flexible traffic control are verified using simulations.

3.1 Basic Assumptions

The next-generation all-optical networks under consideration introduce brand new concepts in the fields of data transmission, switching, and network control. Therefore, the design of this kind of networks should not be restricted by state-of-art technology limitations. Nevertheless, it must still be based on realistic hypotheses. With the reference of previous researchers' work in [Boch04], [Agil05] and [Rama06], the basic ideas in this thesis for the design of agile all-optical metro networks are derived. First of all, the cost of OEO conversions will not be dramatically reduced in the foreseeable future. This is the fundamental assumption for the development of all-optical networks in order to maintain the signal in the optical domain as much as possible. Secondly, with the efforts of researchers and network equipment vendors, it is assumed that the technology of fast-reconfigurable all-optical switches will mature in the near future to be deployable into metro all-optical cores. Thirdly, it is supposed that the time division multiplexing (TDM) on wavelength channels will be achieved soon by solving the critical issue of time synchronization to provide WDM-TDM lightpaths. The technique of further dividing wavelength channels into time-shared sub-channels enables flexible bandwidth allocation and pushes all-optical switches far closer to end users. Last but not least, it is believed that the practical applications of optical memory, optical header cognition and fast wavelength conversion are not realizable in the foreseeable future.

With the above considerations, the assumptions for agile all-optical metro networks in this thesis are summarized as follows:

- Data traffic is maintained in the optical domain while it is transmitted in a network. (No OEO conversion in data paths).
- An all-optical data channel is one or some timeslots in a frame or frames on same wavelengths of fibers spanning all links along a route. The frame repeats in time. (Fast-reconfigurable all-optical switches and WDM-TDM multiplexing technologies).
- Traffic traveling across a network obeys routing constraint, wavelength continuity constraint and slotting constraint. (No wavelength conversion, no optical memory).

3.2 Node architecture and network topology

Network nodes are the basic elements in networks in that the ability of network nodes determines the functionality of networks. Thus, network control, as a part of network function, is implemented by network nodes. On the other hand, network control functionality should be implemented in the design of network nodes.

The objective of this thesis is to investigate the traffic control in agile all-optical metro networks. Here, traffic control is divided into three sub-layers: nodal layer, network layer, and autonomic system layer. At the nodal layer, each network node should be self-managed so that it is able to achieve local optimum. At the network layer, also noted as the inter-nodal layer, each network node should possess the ability to communicate with each other provided with a set of protocols to realize cooperative and competitive interworking. At the autonomic system layer, also known as the inter-network layer, nodes in different networks should be able to form an autonomic network system that provides pervasive network services to end users. This thesis focuses on the traffic control at the network layer.

Meanwhile, with a service oriented design approach invoked here, network control structure is determined by potential user traffic for agility all-optical networks, which is rapid changing in time and flexible and diverse in bandwidth. Processing customer connection requests to the networks locally avoids a large degree of coordination between central nodes and networks nodes, a requirement in centralized networks, so that the control of fast changing traffic can be realized in a timely manner. Hence, an intelligently distributed-controlled network structure is proposed for next-generation all-optical networks in this thesis.

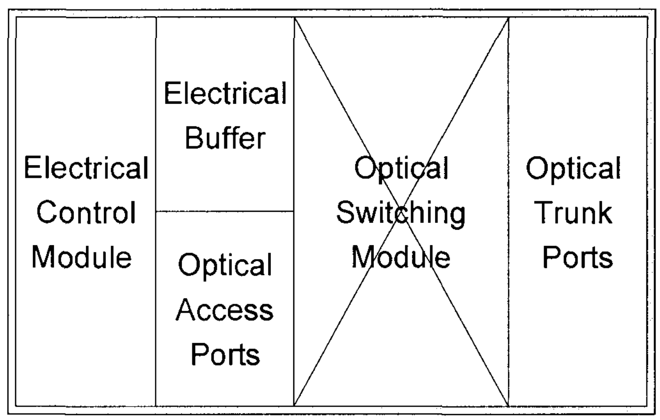


Fig. 3.1 Node Sketch

At the current stage, the design of service oriented all-optical network node has the objective of handling multi-rate highly dynamic traffic with the switching speed at microsecond level. The goal is to accommodate both traditional and newly emerging applications, to maintain the data path entirely in the optical domain in order to speed up data transmission and switching, and to decrease both setup and operational costs. Based on the assumptions in Section 3.1, there is neither optical buffer nor optical header cognition realizable in agile all-optical networks. Thus, it is impracticable to implement all switch functions in the optical domain. For that reason, the traffic routing and control functions in a network node have yet to be implemented in the electrical domain. Consequently, each agile all-optical node has electrical-and-optical hybrid architecture.

As shown in Fig. 3.1, each node has some trunk ports, some access ports, an optical switching module, an electrical control module and electrical buffers. Trunk ports are operating in the optical domain through which switches are connected into networks. Access ports are also operating in the optical domain, and are known as add/drop ports that are responsible for connecting end users into networks. The optical switching module, known as switching fabric, is used to provide fast wavelength add/drop and timeslot operation. With this design, user traffic is kept in the optical domain. Any single data flow starting from an access port of a node is switched to a trunk port of the node by adding the data onto some timeslots or wavelengths. Staying in the same timeslots and wavelengths, it travels through trunk ports and switching fabric of several intermediate nodes, then arrives at a trunk port of its destination node. Finally, it ends at an access port of its destination node by dropping the data from the timeslots and wavelengths carrying the data flow. While the optical parts in the node architecture are responsible for data switching, the electrical parts of each node are implemented for connection operations. Aiming to be an intellectual node in a distributed control structure, the control module in each node controls the operation of dynamic connections in the electrical domain, including request buffering and connection establishment, maintenance, protection and removal. The control module also has the intelligence to manage information that is required for connection operation, such as network discovery, state information exchange, intra-node resource optimization, inter-node cooperation, and self-evolving. The electrical buffers in the node architecture are storage elements for temporary preservation of the connection requests that are waiting for processing. Accordingly, intelligent traffic control will be realized by this hybrid node design.

Compared with long haul networks, metro networks have smaller sizes, diverse services, dynamic and flexible requirements and cost effective equipment. Here, it is proposed that the ring is to be used as the network topology for agile all-optical metro networks. First of all, ring topology has been widely deployed and proven to be superior for metro area networks, e.g. SONET/SDH networks. Secondly, among different network topologies, ring is the minimum-sized 2-connected topology and thus plays an important role in the design of survivable networks. Thirdly, compared with mesh topology, ring topology in a distributed-controlled network requires a lesser degree of coordination between each intelligent network node, and therefore deserves simpler network control function. Lastly, ring networks can form a logical mesh by connecting nodes in one ring with nodes in other rings. On the other hand, it has been shown in [Barr97] that the performance benefit of wavelength conversion in ring networks is relatively small and it drops dramatically with an increase in the number of fibers. This result shows from another perspective that ring topology is good for networks without wavelength conversion.

3.3 Network model and traffic model

The WDM-TDM agile all-optical networks differ from wavelength-routed WDM networks in the following aspects:

- Bandwidth virtualization, where a connection can use only a portion of the bandwidth of a wavelength or, alternatively, the bandwidth of several wavelengths;
- Slotting constraint, where traffic does not change timeslots within a frame along its route.

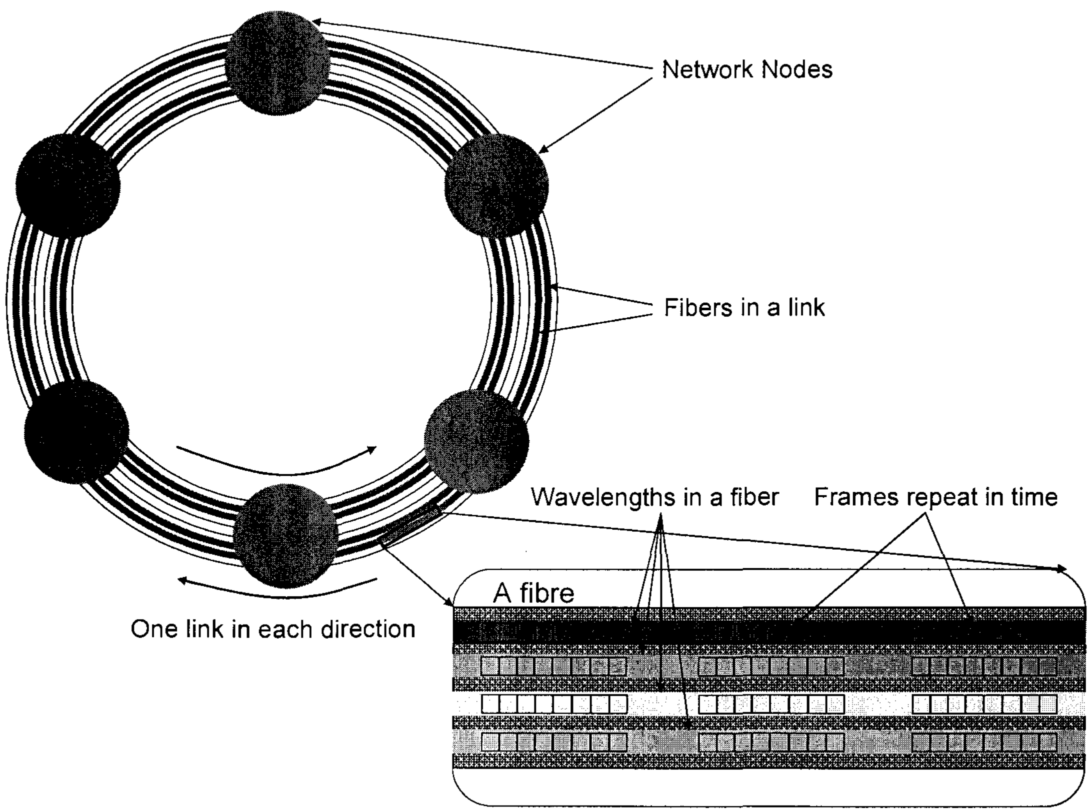


Fig. 3.2 Network Model

As shown in Fig. 3.2, the agile all-optical metro network considered here has a ring topology with N nodes. Fast wavelength reconfiguration and WDM-TDM multiplexing is supported in the network. Every two adjacent nodes are connected by an equal number of fibers, F fibers, in each direction. The network is therefore a bidirectional ring with same link capacity in each direction. Each fiber supports W wavelengths and the bandwidth of each wavelength is partitioned into fixed-length timeslots. A fixed number of timeslots, T timeslots, forms a TDM frame that repeats in time. The bandwidth of one timeslot reflects the minimum possible bandwidth that can be assigned/reserved, and therefore it will be used as the unit for dynamic traffic requests/demands. Note that a demand, a request and a connection request have the same meaning in this thesis.

As it is assumed that the network has neither wavelength conversion nor optical buffers, traffic in the network is subject to the following three constraints: the routing constraint, whereby traffic belonging to one demand will follow the same route; the wavelength continuity constraint, whereby traffic will keep on the same wavelength throughout its path; and the slotting constraint, whereby traffic will stay in the same relative slot position within the frame throughout its path.

To properly reflect the fast changing nature of traffic for all-optical networks, a dynamic traffic model is considered here. Each request/demand is represented by a source node, a destination node and a bandwidth requirement specified in the number of timeslots. Without loss of generality, it is assumed that the bandwidth requirement of each request does not exceed a wavelength capacity, i.e., it is between 1 and T timeslots. It is very easy to extend to super-wavelength cases. For each request/demand, an algorithm assigns a set of timeslots on a wavelength along a path from source node to destination node, i.e., it sets up a lightpath, and carries traffic for the duration of the demand. The connection requests that arrive at each source node are given by Poisson processes with mean arrival rate λ. The destination node of each request is uniformly distributed among the other $N-1$ nodes and the duration of each request is exponentially distributed with mean $1/\mu$. The bandwidth requirement of each request is uniformly distributed in $[1, T]$.

Ch. 4 Flexible Bandwidth Allocation

In agile all-optical metro networks, the potential traffic is characterized by fast-paced change and flexible bandwidth. The bandwidth allocation schemes in this kind of networks, also known as Routing, Wavelength and Timeslot Assignment algorithms, should be well-designed to accommodate traffic according to the parameters of traffic demands and available bandwidths of networks, in order to make good use of network resources in a timely manner. Therefore, dynamic routing, wavelength and timeslot assignment schemes with flexible bandwidth allocation roles are considered here to reflect these attributes of network traffic with the objective of minimizing connection blocking probability. In this thesis, agile all-optical networks are distributed-controlled metro networks with ring topologies. Bandwidth allocation designed here is done primarily by each source node and corresponding destination node with a small degree of cooperation from the intermediate nodes on each connection route.

In single-fiber networks where each link has only two fibers with one fiber in each direction, bandwidth allocation consists of routing, wavelength and timeslot assignment. In multi fiber networks where each link usually has the same number of fibers in each direction, bandwidth allocation includes routing, fiber, wavelength, and timeslot assignment. In this chapter, a novel distributed dynamic routing, wavelength and timeslot assignment scheme for bandwidth on demand in single-fiber networks is proposed in Section 4.1. Section 4.2 introduces and derives a quasi-analytical blocking model for single-fiber networks in order to facilitate network blocking analysis. In Section 4.3, some heuristics of dynamic routing, fiber, wavelength and timeslot assignment for bandwidth on demand in multi-fiber networks are presented and Section 4.4 concludes the chapter.

4.1 A DRWTA algorithm in single-fiber metro ring networks

In networks with ring topologies, there is typically one and only one shortest path for each connection request such that the traffic loads on the links of the lightpath for a connection request are highly correlated. The design consideration behind the Dynamic

Routing, Wavelength and Timeslot Assignment (DRWTA) scheme presented in this section is to pack traffic to already-in-use wavelengths and timeslots in networks in order to leave more free-of-use wavelengths and timeslots for future coming connection requests. The distributed DRWTA scheme proposed here manages network resources in a flexible manner for traffic demands with diverse bandwidth requirements. It also incorporates the concept in dynamic programming to achieve a temporary resource usage optimization, while reducing the run-time of the DRWTA scheme. The performance of the proposed DRWTA scheme is verified via simulation.

To solve the DRWTA problem aimed at ring networks, two concepts are introduced here before going into the detail of the DRWTA scheme: residual wavelengths and residual timeslots. A residual wavelength for a link is defined as the wavelength that is not in use on this link, but is occupied on at least one link in the network. In the same way, a residual wavelength for a path is the wavelength that is free of use on all links of the path, but is busy on at least one link in the network. Similarly, a residual timeslot on a wavelength for a link is defined as the timeslot on the wavelength that is unused on this link, but is used on at least one link in the network. Hence, a residual timeslot on a wavelength for a path is the timeslot on the wavelength that is idle on all links of the path, but is busy on at least one link in the network. With these two concepts, the DRWTA problem is then formulated as a dynamic programming question. Subsequently, the DRWTA algorithm is used to find residual wavelengths and residual timeslots on the shortest path of the current connection request at the current network state. Then, residual wavelengths and residual timeslots are used as much as possible to form the bandwidth for the current connection request in order to free more wavelength and timeslot space for further arriving connection requests, i.e., minimize the total network resource usage. Finally, the simulation tool is employed to evaluate the performance of the algorithm.

Dynamic programming is a recursive approach in solving time-related optimization problems. First of all, divide a problem into stages and find optimum solutions for the last stage problem – a small part of the original problem. Then, enlarge the problem to two stages and find new optimum solutions for the enlarged problem using the previous optimum. Recursively continue in this manner until the problem at hand is enlarged to be the same as the original problem. Finally, trace back from the last stage to the first stage to get an optimum solution for the whole problem.

4.1.1 Computational problem formulation

To define the algorithms, the DRWTA problem should be formulated with network environment parameters, a problem objective and subjected constraints. The network parameters are as follows:

- N nodes connected by N links forming a network with a ring topology;
- *2* fibers for each link with 1 fiber in each direction of a link;
- W wavelengths for each fiber;
- T timeslots for each frame.

As a result, the network is a bidirectional ring. The capacity of each link is $W*T$ per frame time. The network capacity is $2*N*W*T$ per frame time.

The optimization objective of the DRWTA problem is:

- To minimize blocking probability by minimizing network resource usage.

The procedure is subject to the following constraints:

- Routing constraint – do not split one demand,
- Wavelength continuity – no wavelength conversion,
- Slotting constraint – each unit stays in the same timeslot within a frame along its path,
- Bandwidth constraint – without generality, it is assumed that the bandwidth requirement of each connection request is less than the capacity of a wavelength. This constraint is added mainly because current per wavelength capacity is more than enough for almost all network applications. Moreover, the constraint can be easily removed with a slight change in the algorithm.

4.1.2 Distributed DRWTA algorithm

The optimization question formulated above is very difficult to answer if it is treated as one problem. To enable real time bandwidth allocation, i.e., to simplify the problem solution, the DRWTA algorithm here is to decouple the DRWTA problem into three sub-problems and to solve them one-by-one.

- Routing sub-problem, with the objective of minimizing the usage of network resources;
- Wavelength assignment sub-problem, with the objective of minimizing the number of wavelengths in use within the network;
- Timeslot assignment sub-problem, with the objective of minimizing the number of busy timeslots in the network.

The routing sub-problem is the first sub-problem to be identified and unraveled. As stated earlier, the objective of the routing sub-problem is to minimize network resource usage. For a certain connection request in a network with a ring topology, the shorter the path, the lesser the network resources usage. Therefore, the solution for this sub-problem is the shortest path algorithm; i.e., to select the path with the fewest hops in ring networks. The number of hops on the shortest path for a connection request is denoted as n.

Grounded on the routing solution, the wavelength assignment sub-problem is formed and solved in turn. The objective of this sub-problem is to minimize the number of wavelengths in use within the whole network by finding residual wavelengths on the previously determined shortest path that has n hops. The residual wavelengths at stage t of the algorithm, where t is between 1 and n, are those wavelengths that are not occupied in any links from hop n to hop t on the shortest path of the connection request. The dynamic programming algorithm is formed as follows:

- Stage t: links from hop n to hop t along the shortest path ($n \ge t \ge 1$).
- State: the number of residual wavelengths at stage t (i.e., after n-t iterations).
- Decision: residual wavelengths at the current stage.
- Decision update to state: calculate the residual wavelengths.
- Recursive value relationship: $e_n = a_n \cap g_{WL}$ and $e_t = a_t \cap e_{t-1}$, $n \ge t \ge 1$,

  where

  e_t: set of residual wavelengths at stage t;

a_t: set of available wavelengths on the link of hop t, local information;

g_{WL}: set of wavelengths occupied in the network, global information.

Based on the results from the previous two sub-problems, the timeslot assignment sub-problem can now be formulated and solved. The objective of this sub-problem is to minimize the number of busy timeslots in the whole network by searching residual timeslots on wavelengths that are used, but have enough timeslots for the current connection request. Similar to the previous sub-problem, the residual timeslots at stage t of the algorithm, where t is between 1 and n, are the timeslots that are not used on wavelengths of any link from hop n to hop t on the shortest path of the connection request. The following is the algorithm:

- Stage t: links from hop n to hop t along the shortest path ($n \geq t \geq 1$).
- State: number of residual timeslots for wavelengths under investigation (wavelengths that have enough timeslots for the current demand).
- Decision: residual timeslots at the current stage.
- Decision update to state: calculate the residual timeslots for each wavelength. If the total available timeslots for a wavelength are less than the timeslot requirement of the current bandwidth demand, then purge the wavelength.
- Recursive value relationship: $f_n = b_n \cap g_{TS}$ and $f_t = b_t \cap f_{t-1}$, $n \geq t \geq 1$

  where

  f_t: set of residual timeslots at stage t;

  b_t: set of available timeslots for each wavelength under investigation on the link of hop t, local information;

  g_{TS}: set of timeslots used on wavelengths in the network, global information.

Finally, the solution for the original problem (assigning bandwidth to a connection request) is built by tracing back the results of the three sub-problems. Considering the routing, wavelength continuity and slotting constraints, residual timeslots and/or wavelengths are used first. This is to minimize the number of timeslots and wavelengths used in the network, i.e., to minimize network resource usage. This in turn reduces blocking probability in networks with ring topologies. Let R_w denote the number of residual timeslots in wavelength w along the shortest path p of the connection request. Non-residual wavelengths refer to the wavelengths that are not residual wavelengths but having some residual timeslots. The set of non-residual wavelengths on the shortest path p that have sufficient residual timeslots for the demand is denoted by S_{NRW}; the set of residual wavelengths on the shortest path p that have sufficient residual timeslots for the demand is denoted by S_{RW}; and the set of wavelengths on the shortest path p that have enough number of idle timeslots for the demand with some but not enough residual timeslots is denoted by S_{WR}. The final stage of the DRWTA algorithm for the current connection request is as follows:

- If $S_{NRW} \neq \varnothing$

  Then choose the non-residual wavelength w so that

  $$\min_{w \in S_{NRW}} R_w$$

  And then assign timeslots to the demand from these residual timeslots on the non-residual wavelength.

- Else if $S_{RW} \neq \varnothing$

  Then select the residual wavelength w so that

  $$\min_{w \in S_{RW}} R_w$$

  And then assign timeslots to the demand from these residual timeslots on the residual wavelength.

- Else if $S_{WR} \neq \varnothing$

  Then, choose the wavelength w so that

  $$\max_{w \in S_{WR}} R_w$$

  And then assign these residual timeslots to the demand first, and select the rest of the timeslots for the demand from globally available timeslots on the wavelength.

- Else, if there exist wavelengths in use in the network that have a sufficient number of idle timeslots for the demand

Then select the wavelength that has the minimum amount of free bandwidth that is sufficient for the demand; assign timeslots to the demand from these globally available timeslots on the wavelength.

- Else, if globally idle wavelengths exist

  Then choose the first-fit idle wavelength; assign timeslots on the wavelength to the demand.

- Else

  The connection request is blocked.

4.1.3 Simulation and analysis

The performance of the proposed algorithm is evaluated through simulation by comparing it to the performance of the Random algorithm, which utilizes shortest path routing with random wavelength and timeslot assignment. The random wavelength and timeslot assignment algorithm randomly selects timeslots on a randomly selected wavelength that has enough bandwidth for a connection request. A dynamic connection request model is considered, where the requests arrival at each node with Poisson processes and the destination node of each request is uniformly distributed among the other *N-1* nodes. Each node has its own arrival rate with mean values of $\lambda_i, i = 1, 2, ..., N$. The duration of each request is exponentially distributed with mean $1/\mu$. The bandwidth requirement of each random incoming request is uniformly distributed in *[1, T]*. All the figures below show the average blocking probability per request for 10 replications with 1 million random requests each. In this section, the 95% confidence intervals of all simulation results are between ±3.7% of the results when network load is light and are between ±0.2% of the results when network load is high.

Fig. 4.1 compares the blocking performance versus the average network load for the proposed algorithm ("Residue") and the algorithm of random wavelength and timeslot assignment ("Random") along the shortest path for the following network parameters: $N = 16$, $W = 8$, and $T = 8$. The figure shows that the blocking probability for the network increases with the increase of network load. The proposed algorithm outperforms the Random algorithm in the whole network load range and presents much better performance than the Random algorithm when the network is either light loaded or heavily loaded. When a network is light loaded, blocking is primarily caused by the wavelength continuity constraint and the slotting constraint. The proposed algorithm tries to decrease the blocking caused by these constraints through the method of leaving more global free-of-use wavelengths and timeslots for further arriving connection requests. When a network is heavily loaded, network blocking is mainly coming from the shortage of network resources. The proposed algorithm utilizes the wavelength continuity constraint and the slotting constraint to pack traffic together to minimize network resource usage in order to decrease network blocking.

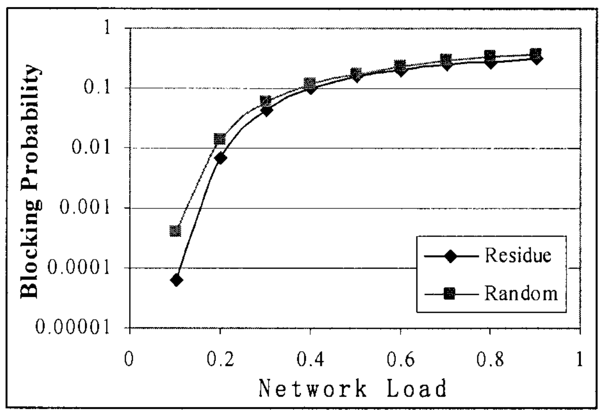


Fig. 4.1. Blocking probability vs. network load.

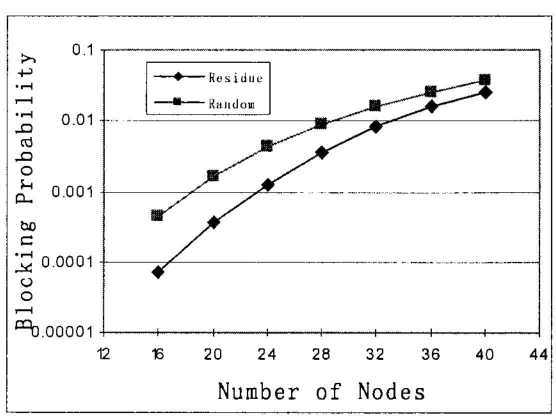


Fig. 4.2. Blocking probability vs. number of nodes

Fig. 4.2 shows the blocking performance versus number of network nodes for $W = 8$, $T = 8$ when network traffic load is 10% of the network capacity. It can be observed that the increase in the number of nodes in a network has similar effect on network blocking performance as the increase of network traffic load. The proposed algorithm has much better performance than the Random algorithm.

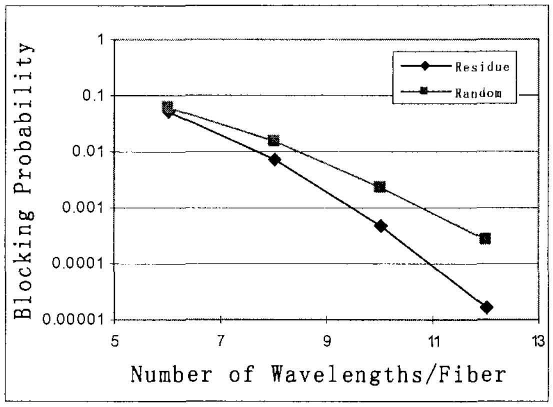


Fig. 4.3. Blocking probability vs. number of wavelengths per fiber.

Fig. 4.3 illustrates the blocking performance versus number of wavelengths per fiber for $N = 16$ and $T = 8$, when network traffic load is 20% of the network capacity. With the linear increase in number of wavelengths per fiber, the network capacity increases linearly and the blocking probability decreases drastically. The performance benefits from the proposed algorithm are more and more significant with the increase of the number of wavelengths per fiber.

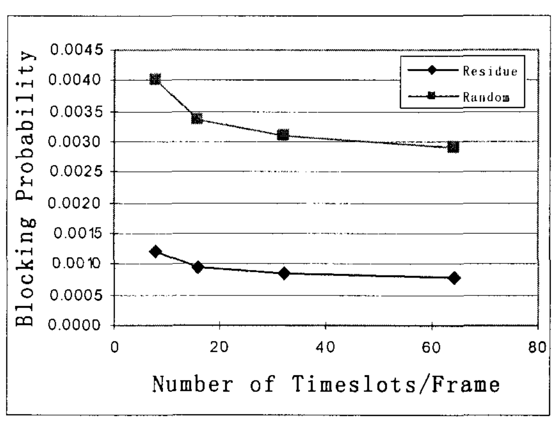


Fig. 4.4. Blocking probability vs. number of timeslots per frame

Fig. 4.4 presents the blocking performance versus number of timeslots per frame: $N = 16$ and $W = 8$, when network traffic load is 15% of the network capacity. Since the bandwidth demand of each dynamic request is modeled as uniformly distributed in $[1, T]$, the increase of the number of timeslots per frame does not have a major impact on the blocking probability. It exhibits, however, a slight decrease in blocking because the increase of number of timeslots per frame provides more flexibility in timeslot assignment. The figure also shows that the increase of the number of timeslots per frame has similar effects on the two algorithms. Nevertheless, the proposed algorithm has much better blocking performance than the Random algorithm.

4.1.4 Optimization criterion in the distributed DRWTA algorithm

In section 4.1.2, the optimization criterion in the algorithm at the stage of final decision making, reached by tracing back the results of the three sub-problems, is:

$$\min_{w \in S_{NRW}} R_w \text{ or } \min_{w \in S_{RW}} R_w,$$

when sufficient number of residual timeslots exist on non-residual or residual wavelengths, respectively. Aiming to leave more residual timeslot space for further incoming demands, the wavelength assignment scheme chooses the non-residual or residual wavelength that has the minimum number of residual timeslots among non-residual or residual wavelengths that have sufficient number of residual timeslots for each demand, when these kinds of wavelengths are available. As a result, the algorithm has a much better performance than the Random algorithm. Table 4.1 shows the simulation results of the algorithm proposed in Section 4.1.2 for the following network parameters: $N = 16$, $W = 8$, and $T = 8$, which presents the rates of demand distribution among 1 million demands that 1) all timeslots of the demand using residual timeslots; 2) some timeslots using residual timeslots; 3) using globally idle timeslots on an existing in use wavelength; 4) using globally idle timeslots on a globally idle wavelength. The 95% confidence intervals of all simulation results in the table are less than the range of ±0.7% of the results. The rate of case 1) increases rapidly and reaches its peak when network load goes between 30% and 40% of network capacity. It decreases steadily afterwards. The rate of case 2) decreases gradually with the increase of network load. The rate of case 3) stays almost in a same level with a slight decrease as network load increases while the rate of case 4) decreases drastically with the increase of network load. Demands that are totally or partially assigned with residual timeslots are roughly between 70% and 80% in which demands that are totally assigned with residual timeslots are approximately between 60% and 70%. Therefore, the optimization criterion in the algorithm at the stage of final decision making, reached by tracing back the results of the three sub-problems, plays an important role in the algorithm and therefore has an impact on network blocking.

Table 4.1 Rates of demand distribution among 1 million demands

Network load	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
All timeslots using residual timeslots	0.554	0.663	0.697	0.695	0.680	0.663	0.645	0.628	0.612
Some timeslots using residual timeslots	0.157	0.143	0.134	0.123	0.110	0.096	0.083	0.072	0.062
Sub Total	0.711	0.806	0.831	0.818	0.791	0.759	0.728	0.700	0.673
New timeslots on existing in use wavelength	0.094	0.063	0.050	0.042	0.035	0.030	0.025	0.021	0.018
New timeslots on new wavelength	0.195	0.124	0.075	0.039	0.019	0.010	0.005	0.003	0.001
Total	1.000	0.993	0.956	0.899	0.845	0.798	0.758	0.723	0.693

Considering the characteristics of agile all-optical networks, traffic demands are highly dynamic. Some wavelengths or timeslots that are busy at a specific time may soon become idle. Hence, some wavelengths or timeslots may be the residual wavelengths or timeslots at the time that a demand comes into a network, and the proposed wavelength and timeslot assignment algorithm is executed to assign a wavelength and timeslots to the demand. An issue here is that these wavelengths or timeslots may no longer have the meaning of "residual" to the demand when the demand is still served by the network. Therefore, it can be seen that the DRWTA algorithm proposed in Section 4.1.2 can be improved by properly choosing an optimization criterion for the algorithm in considering the issue. To deal with this issue, it is proposed here to check the utilization of the residual timeslots. The utilization of a residual timeslot is defined here as the number of demands, which are existing in a network, that use the timeslot.

The optimization criterion proposed in Section 4.1.2 is denoted as Criterion 0. Three additional optimization criteria are presented here. Instead of focusing on leaving more residual space for further incoming demands, the primary concern of Criterion 0, Criterion 1 aims to keep the residual wavelengths or timeslots of a demand in a network staying "residual" when the demand is alive in the network. This is done through choosing the most-loaded residual wavelength and residual timeslots. Let t be the number of timeslots that is needed by a connection request. The load of a timeslot is defined as 1 when there is one live connection in the network using the timeslot. Let L_w denote the total load of the first t residual timeslots of a wavelength.

Criterion 1: The most-loaded wavelength w on the shortest path that achieves

$$\max_w L_w .$$

Criterion 2 is the same as Criterion 1 when there are wavelengths on the shortest path of a connection request that have a sufficient number of residual timeslots for the connection request. It tries to make a compromise between the total load of residual timeslots on a wavelength and the total number of residual timeslots on the wavelength when no wavelength on the shortest path of a connection request has a sufficient number of residual timeslots for the connection request. As defined in Section 4.2.1, R_w denotes the number of residual timeslots in wavelength w along the shortest path p of the connection request.

Criterion 2: The most-loaded wavelength w on the shortest path that achieves

$$\max_w L_w ,$$

when some wavelengths have more than t residual timeslots on the shortest path of the connection request; or the wavelength w on the shortest path that achieves

$$\max_w (L_w + R_w) .$$

Criterion 3 tends to make a compromise between Criterion 0 and Criterion 1. It is likely to use the most-loaded wavelength while trying to leave more residual timeslot space for further incoming demands when some wavelengths have more than t residual timeslots on the shortest path of the connection request. It is the same as Criterion 2 when no wavelength on the shortest path of a connection request has a sufficient number of residual timeslots for the connection request.

Criterion 3: The wavelength w on the shortest path that achieves

$$\max_w (L_w + t - R_w)$$

when some wavelengths have more than t residual timeslots on the shortest path of the connection request; or the wavelength w on the shortest path that achieves

$$\max_{w}(L_w + R_w).$$

Replacing Criterion 0 with Criterion 1, the final stage of the DRWTA algorithm proposed in Section 4.1.2 is changed as follows:

- If $S_{NRW} \neq \varnothing$

  Then choose the non-residual wavelength w such that

  $$\max_{w \in S_{NRW}} L_w$$

  And then assign timeslots to the demand from these residual timeslots on the non-residual wavelength.

- Else if $S_{RW} \neq \varnothing$

  Then select the residual wavelength w such that

  $$\max_{w \in S_{RW}} L_w$$

  And then assign timeslots to the demand from these residual timeslots on the residual wavelength.

- Else if $S_{WR} \neq \varnothing$

  Then choose the wavelength w such that

  $$\max_{w \in S_{WR}} L_w$$

  And then assign these residual timeslots to the demand first, and select the rest of the timeslots for the demand from globally available timeslots on the wavelength.

- Else, if there are some wavelengths in use in the network that have a sufficient number of idle timeslots for the demand

  Then select the wavelength that has the minimum amount of free bandwidth that is sufficient for the demand; assign timeslots to the demand from these globally available timeslots on the wavelength.

- Else, if there are some globally idle wavelengths

  Then choose the first-fit idle wavelength; assign timeslots on the wavelength to the demand.

- Else

  The connection request is blocked.

Replacing Criterion 0 with Criterion 2, the final stage of the DRWTA algorithm proposed in Section 4.1.2 is changed as follows:

- If $S_{NRW} \neq \varnothing$

  Then choose the non-residual wavelength w such that

  $$\max_{w \in S_{NRW}} L_w$$

  And then assign timeslots to the demand from these residual timeslots on the non-residual wavelength.

- Else if $S_{RW} \neq \varnothing$

  Then select the residual wavelength w such that

  $$\max_{w \in S_{RW}} L_w$$

  And then assign timeslots to the demand from these residual timeslots on the residual wavelength.

- Else if $S_{WR} \neq \varnothing$

  Then choose the wavelength w such that

  $$\max_{w \in S_{WR}} (L_w + R_w)$$

  And then assign these residual timeslots to the demand first and select the remaining timeslots for the demand from globally available timeslots on the wavelength.

- Else, if there exist some wavelengths in use in the network that have enough number of idle timeslots for the demand

  Then select the wavelength that has minimum amount of free bandwidth that is sufficient for the demand; assign timeslots to the demand from these globally available timeslots on the wavelength.

- Else, if there exist some globally idle wavelengths

  Then choose the first-fit idle wavelength; assign timeslots on the wavelength to the demand.

- Else

  The connection request is blocked.

Replacing Criterion 0 with Criterion 3, the final stage of the DRWTA algorithm proposed in Section 4.1.2 is changed as follows:

- If $S_{NRW} \neq \varnothing$

  Then choose the non-residual wavelength w such that

  $$\max_{w \in R_{NRW}} (L_w + t - R_w)$$

  And then assign timeslots to the demand from these residual timeslots on the non-residual wavelength.

- Else if $S_{RW} \neq \varnothing$

  Then, select the residual wavelength w such that

  $$\max_{w \in R_{RW}} (L_w + t - R_w)$$

  And then assign timeslots to the demand from these residual timeslots on the residual wavelength.

- Else if $S_{WR} \neq \varnothing$

  Then, choose the wavelength w such that

  $$\max_{w \in S_{WR}} (L_w + R_w)$$

  And then assign these residual timeslots to the demand first, and select the rest of the timeslots for the demand from globally available timeslots on the wavelength.

- Else, if there are some wavelengths in use in the network that have a sufficient number of idle timeslots for the demand

  Then, select the wavelength that has the minimum amount of free bandwidth that is sufficient for the demand; assign timeslots to the demand from these globally available timeslots on the wavelength.

- Else, if there are some globally idle wavelengths

  Then, choose the first-fit idle wavelength; assign timeslots on the wavelength to the demand.

- Else

  The connection request is blocked.

The performances of the DRWTA algorithm with the three newly proposed criteria are evaluated through simulation and are compared with the result of the DRWTA algorithm applying Criterion 0 for the following network parameters: $N = 16$, $W = 8$, and $T = 8$. The blocking probabilities of the DRWTA algorithm with the four criteria are shown in Table 4.2. The sizes of the 95% confidence intervals of the simulation results in the table are decreased from ±3.6% of the value of the results to ±0.2% of the value of the results when traffic load increases from 30% of network capacity to 90% of network capacity. The DRWTA algorithm with Criterion 3 has the best performance. Table 4.3 shows the maximum number of live connections in networks. The 95% confidence intervals of all simulation results in the table are less than the range of ±0.8% of the results. The maximum number of live connections in networks increases when network traffic load rises. The DRWTA algorithm with Criterion 3 has a somewhat higher number of live connections in networks.

Table 4.2 Blocking probabilities of the DRWTA algorithm with the four criteria

Network Load	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Criterion 0	6.128E-05	6.802E-03	4.440E-02	1.006E-01	1.546E-01	2.016E-01	2.419E-01	2.767E-01	3.072E-01
Criterion 1	5.825E-05	6.331E-03	4.197E-02	9.780E-02	1.527E-01	2.004E-01	2.413E-01	2.764E-01	3.067E-01
Criterion 2	5.757E-05	6.356E-03	4.202E-02	9.787E-02	1.526E-01	2.004E-01	2.412E-01	2.765E-01	3.068E-01
Criterion 3	5.832E-05	6.286E-03	4.148E-02	9.643E-02	1.505E-01	1.979E-01	2.387E-01	2.739E-01	3.046E-01

Table 4.3 The maximum number of live connections in networks

Network Load	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Criterion 0	33.84	51.09	64.13	74.26	83.65	91.54	98.99	105.91	112.02
Criterion 1	34.01	50.97	64.08	74.46	83.86	92.06	98.87	106.11	112.12
Criterion 2	33.95	51.39	64.11	74.94	83.75	91.86	99.27	106.15	111.86
Criterion 3	33.97	51.01	64.43	74.96	83.96	92.17	99.25	106.37	112.48

The rates of demands with all timeslots using residual timeslots are shown in Table 4.4 and the rates of demands with some or all timeslots using residual timeslots are shown in Table 4.5. The 95% confidence intervals of all simulation results in the table are lesser than the range of ±0.18% of the results. Shown in the tables, the DRWTA algorithm with Criterion 0, proposed in Section 4.1.2, has the highest rates, which implies that it has the highest possibility to accommodate demands on residual wavelengths and timeslots. However, it still has the highest blocking probability among the four criteria. This result proves that the consideration in this section, which composes the criteria for the investigation of the highly changing characteristic of traffic in agile all-optical networks, is the right direction for the research. Among the three criteria proposed in this section, the DRWTA algorithm with Criterion 3 has the highest rate of all-on-residual demands. It has a slightly higher rate of all- and partial-on-residual demands than the other two criteria, which implies it has a little lower rate of partial-on-residual demands than the other two criteria. This result suggests that the DRWTA algorithm with Criterion 3 utilizes residual bandwidths more efficiently than the other two Criteria. Therefore, the DRWTA algorithm designed in Section 4.1 is the algorithm for which the first several steps are detailed in Section 4.1.2, and the final stage is the scheme using Criterion 3 presented in Section 4.1.4.

Table 4.4 Rates of all-on-residual demands

Network Load	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Criterion 0	0.5544	0.6630	0.6972	0.6949	0.6803	0.6625	0.6449	0.6279	0.6118
Criterion 1	0.5479	0.6491	0.6796	0.6752	0.6583	0.6388	0.6200	0.6024	0.5863
Criterion 2	0.5477	0.6488	0.6793	0.6748	0.6580	0.6387	0.6199	0.6022	0.5861
Criterion 3	0.5511	0.6555	0.6881	0.6850	0.6689	0.6499	0.6309	0.6130	0.5963

Table 4.5 Rates of all-on-residual and partial-on-residual demands

Network Load	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Criterion 0	0.7113	0.8062	0.8307	0.8183	0.7906	0.7590	0.7282	0.6995	0.6733
Criterion 1	0.7057	0.7965	0.8218	0.8119	0.7860	0.7558	0.7257	0.6976	0.6720
Criterion 2	0.7057	0.7967	0.8219	0.8119	0.7860	0.7558	0.7258	0.6975	0.6719
Criterion 3	0.7069	0.7978	0.8224	0.8122	0.7866	0.7566	0.7266	0.6986	0.6727

Table 4.6 Blocking probabilities of the First-Fit and the DRWTA algorithms

Network Load	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
First-Fit	6.765E-05	6.854E-03	4.247E-02	9.721E-02	1.518E-01	2.000E-01	2.413E-01	2.769E-01	3.079E-01
Residue	5.832E-05	6.286E-03	4.148E-02	9.643E-02	1.505E-01	1.979E-01	2.387E-01	2.739E-01	3.046E-01

Table 4.6 compares the blocking performance of the proposed DRWTA algorithm ("Residue") and the algorithm of first-fit wavelength and timeslot assignment ("First-Fit") along the shortest path for the following network parameters: $N = 16$, $W = 8$, and $T = 8$. The sizes of the 95% confidence intervals of the simulation results in the table are decreased from ±3.5% of the results to ±0.2% of the results when traffic load increases

from 30% of network capacity to 90% of network capacity. The proposed DRWTA algorithm performs slightly better than the widely used First-Fit algorithm.

In conclusion, a DRWTA algorithm is presented in Section 4.1 to support dynamic flexible bandwidth on demand in WDM/TDM all-optical ring networks. The algorithm introduces the concepts of residual wavelengths and residual timeslots to minimize the blocking probability with the knowledge of global link-state information and applies the dynamic programming technique to reduce the runtime for the optimization. The algorithm is simple and is ready to scale to multiple fiber cases, as the runtime increases only linearly. Since the algorithm purges the wavelengths that are not applicable for the setup of each connection request, the asymptotic estimate of the computational complexity of the proposed dynamic RWTA algorithm is $O(NWT\log(WT))$. Simulation results show that, with only a tiny increase in runtime, the performance of the proposed algorithm has made significant improvement compared to the scheme of random wavelength and timeslot assignment along the shortest path and is slightly better than the First-Fit wavelength and timeslot assignment algorithm.

4.2 Analytical model for single-fiber networks

As a powerful means of evaluation in the performance of a network design, simulations still require a great deal of effort in problem formulation, objective setup, model conceptualization, data collection, model translation, validation and verification, experimental design, simulation execution, and output analysis [Bank00]. These efforts can be eliminated if a mathematical model is available. In this section, a quasi-analytical model regarding network blocking performance of a DRWTA algorithm is developed for single-fiber ring networks, where every two adjacent nodes are connected by two fibers, one in each direction. The network is therefore a bidirectional ring with a single fiber link capacity in each direction. The effectiveness of the quasi-analytical model is evaluated via simulation.

4.2.1 Analytical model and initial values

Compared with the mathematical models proposed in literature for RWA algorithms, there are two technical difficulties for the development of mathematical models for DRWTA algorithms: flexible bandwidth assignment rather than unique bandwidth assignment, and an additional level of assignment – wavelength assignment and timeslot assignment rather than wavelength assignment only. On the other hand, the ring topology is considered here, which makes modeling of DRWTA algorithms simpler. Notwithstanding, the analytical model proposed here is based on a simplified DRWTA algorithm where the DRWTA problem is decomposed into a routing subproblem and a wavelength and timeslot assignment subproblem. For ring networks, shortest path routing utilizes minimum network resources. Thus, for the routing subproblem of the DRWTA problem, the shortest path routing is selected as the routing scheme to dynamically accommodate connection requests. For the wavelength and timeslot assignment subproblem of the DRWTA problem, a random assignment scheme is chosen to facilitate the blocking performance analysis, since it makes the wavelength assignment and the timeslot assignment problems independent of each other. Another reason to pick random wavelength and timeslot assignment algorithm is that the performance of random assignment algorithms is in the middle of the performance of packed assignment schemes and spreading assignment schemes, as illustrated in the literature review, meaning that the model can be an approximate measure of network blocking performance.

With the simplified DRWTA algorithm defined above, a model is developed here to calculate network blocking probability step by step for WDM-TDM all-optical single-fiber bidirectional ring networks. The analysis is based on the following assumptions.

- Blocked connection requests are discarded;
- Network traffic is uniformly distributed between network nodes.
- Wavelength assignment and timeslot assignment are independent between adjacent links (hops), i.e., the probability that a timeslot on a wavelength is busy in a hop link is independent of the probability that the timeslot on the wavelength is busy in its adjacent hop link;

- Timeslot assignment is independent between the timeslots on a wavelength for one connection request;
- Shortest path routing is used to minimize resource usage in ring networks;
- The wavelength and timeslots assigned to a request are randomly chosen from idle wavelengths and their idle timeslots. Idle wavelengths are defined to be wavelengths that have enough idle timeslots for the current connection request.

Analytical problem formulation:

Given: average network traffic load

Given in the form of a percentage of total network capacity

Objective: calculate network blocking probability

Network blocking probability for the Random DRWTA algorithm

Suppose a dynamic request needs K timeslots and will travel H hops from source node to destination node with shortest path routing, where K is a random variable uniformly distributed in $[1,T]$ and H is a random variable determined by the shortest path routing algorithm. Since it is assumed that the wavelength and timeslot assignment on different links are independent and it is assumed that network traffic is uniformly distributed between network nodes, for a certain network load, the probability that a timeslot on a wavelength is busy in one link is the same as the probability that the timeslot on the wavelength is busy in any other link in the network. Likewise, with the assumption that timeslot assignment for the timeslots of a connection request is independent of each other on a wavelength of a hop link, for a certain network load, the probability that a timeslot on a wavelength is busy in one hop link is the same as the probability that another timeslot on the wavelength is busy in the hop link in the network. Based on the above analysis, let p be the probability that a timeslot on a wavelength is used on a hop. Then, the probability that a timeslot is free on H hops is $(1-p)^H$. As it is specified in the network model, a TDM frame is formed by T timeslots. The probability that a fixed set of K timeslots are free and the other $T-K$ timeslots are used on a wavelength for H hops is

$$((1-p)^H)^K (1-(1-p)^H)^{T-K}.$$

Thus, the probability that exactly K timeslots on a wavelength are free on all H hops from source node to destination node is

$$C(T,K)((1-p)^H)^K(1-(1-p)^H)^{T-K};$$

where $C(T,K)$ is the number of possible combinations that K timeslots are free on a wavelength with T timeslots per TDM frame.

Let X be a random variable defined as 0 when a dynamic request can be set up on a wavelength and 1 when it cannot be set up. The probability that a request can be set up on a wavelength conditioned on that it needs K timeslots and will travel H hops is

$$P_r(X=0 \mid K,H)=\sum_{i=K}^{T} C(T,i)((1-p)^H)^i(1-(1-p)^H)^{T-i}. \quad (1)$$

The probability that a request can be set up on a wavelength in a network with N nodes:

$$P_r(X=0)=\sum_{k=1}^{T}\{\sum_{h=1}^{N/2} P_r(X=0 \mid K,H)P_r(H=h)\}P_r(K=k), \quad (2)$$

when N is even; or

$$P_r(X=0)=\sum_{k=1}^{T}\{\sum_{h=1}^{(N-1)/2} P_r(X=0 \mid K,H)P_r(H=h)\}P_r(K=k), \quad (3)$$

when N is odd; where $P_r(K=k)$ is the probability that a dynamic request needs k timeslots and $P_r(H=h)$ is the probability that a request will travel h hops. Then, the network blocking probability Pb, i.e., the probability that a request cannot be set up on any wavelength, is

$$Pb=(1-P_r(X=0))^W. \quad (4)$$

As the bandwidth requirement of each random request is uniformly distributed in $[1,T]$, the probability that a request needs k timeslots is

$$P_r(K=k)=1/T,\ k=1,2,...T.$$

In ring networks, by applying the assumption of shortest path routing, the probability that a request will travel h hops is

$$P_r(H=h)=2/(N-1),\ h=1,2,...(N/2-1),$$

$$P_r(H=h)=1/(N-1),\ h=N/2,$$

when N is even; or

$$P_r(H = h) = 2/(N-1)\,,\ h = 1,2,...(N-1)/2\,,$$

when N is odd.

In brief, if the probability p, the probability that a timeslot on a wavelength is used on a hop, is given, then the network blocking probability can be calculated with the equation (1), (2) or (3), and (4). The next step is to derive the value of probability p from the given parameter, network traffic load.

From the network and traffic model assumptions described in Chapter 3, the capacity of the bidirectional ring network is $2NWT$. When the average offered load to each network node is λ/μ and network traffic is uniformly distributed among N nodes, the average network load is $N(N/4)(T/2)(\lambda/\mu)$, where the average number of hops a dynamic request travels is roughly $N/4$ [1] and the average number of timeslots a request needs is about $T/2$ [2]. Thus, a practical approximation of the value of probability p, the probability that traffic is carried in a timeslot of a wavelength of a link in a network, can be derived as the average network load divided by the total network capacity:

$$p_0 \approx (\lambda N)/(16\mu W)\,. \qquad (5)$$

However, it is observed that the blocking probability Pb_0 calculated using p_0 overestimates the network blocking probability because it does not consider those requests that have already been blocked. In fact, network blocking probability Pb and the probability p are coupled with each other, in that network blocking determines the amount of traffic that can be carried in a network, and the amount of traffic carried in a network in turn determines network blocking. Iteration is a typical scheme to break this nonlinear relationship between these two system parameters in order to have the problem solved. To derive an accurate value for the network blocking performance, the following iterative function is proposed here for the computation of probability p :

[1] Exactly $N/4$ when N is even and $(N/4 - 1/4N)$ when N is odd.

[2] Exactly $(T+1)/2$.

$$p_i = p_{i-1}(1 - Pb_{i-1}). \quad (6)$$

4.2.2 Algorithm for computing network blocking probability

From the analysis in Section 4.2.1, an iterative algorithm is developed here with the method of repeated substitution. The algorithm to iteratively obtain the network blocking probability from a given network traffic load for ring networks, with shortest path routing and random wavelength and timeslot assignment algorithm, is shown below in detail:

1) $i=0$;
2) Initialize the probability that traffic is carried in a timeslot of a wavelength of a link in a network p_i using equation (5);
3) Initialize network blocking probability Pb_i. First, use equation (1), then use equation (2) when the number of network node N is even, or equation (3) when N is odd. Finally use equation (4);
4) $i = i+1$;
5) Update p_i using (6);
6) Calculate network blocking probability Pb_i at iteration i. First, use equation (1), then use equation (2) when the number of network node N is even, or equation (3) when N is odd. Finally use equation (4);
7) If $|Pb_i - Pb_{i-1}| < \varepsilon$, then terminate; else go to step 4.

The algorithm above concludes the quasi-analytical model for the analytical problem defined in section 4.2.1

4.2.3 Comparison of analytical and simulation results

The effectiveness of the proposed quasi-analytical model in the evaluation of network blocking probability is verified through simulation. In this section, the 95% confidence intervals of all simulation results are between ±3% of the results when network load is light and are between ±0.3% of the results when network load is high.

Fig. 4.5 plots the blocking probability versus offered network traffic load and compares the network blocking performance obtained using the analysis model with simulation results. The DRWTA algorithm used in both the quasi-analytical calculation and network simulation is shortest path routing with random wavelength and timeslot assignment algorithms. The lower two curves show the quasi-analytical and simulation results for the case of $N=16$, $W=8$ and $T=8$, while the upper two curves show the quasi-analytical and simulation results for the case of $N=24$, $W=8$ and $T=8$. The figure indicates that the proposed method for network blocking performance evaluation is quite accurate for the case of network load between 30% and 70%, which represents the most popular network load conditions in real-world operating networks. There are some slight differences between quasi-analytical blocking results and simulation results when networks are either light loaded or heavily loaded.

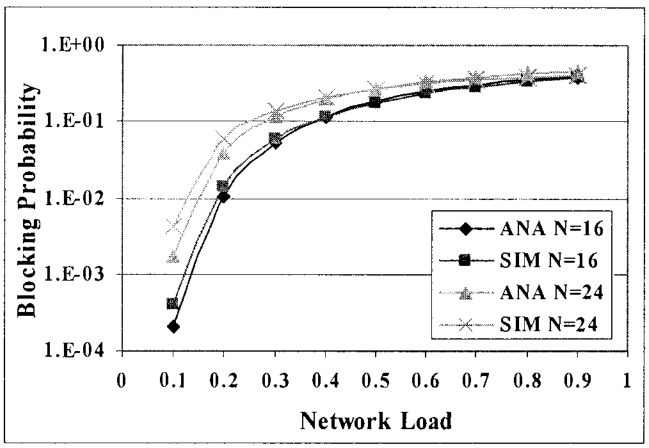


Fig. 4.5. Blocking probabilities: quasi-analytical and simulation results for W=8 T=8.

In fact, the model assumes that wavelength assignment and timeslot assignment on different links are independent, and assumes that timeslot assignment is independent on different timeslots on a wavelength. However, these assumptions do not accurately reflect network conditions because of the load correlation introduced by the wavelength continuity constraint and the slotting constraint between adjacent links, which is denoted as link-load correlation here, and the load correlation introduced by the flexible bandwidth allocation between the timeslots on a wavelength for each connection request, which is denoted as timeslot-batch correlation. These correlations, which span two dimensions, result in minor inaccuracy of the proposed independent quasi-analytical model in light-loaded and heavy-loaded network conditions. The two dimensional characteristic of the correlations also make the derivation of an analytical model with the consideration of these correlations extremely complicated.

On the other hand, Fig. 4.5 shows that link-load correlation and timeslot-batch correlation result in less blocking than expected with the proposed independent quasi-analytical model, when a network is heavily loaded where call blocking is primarily caused by inefficient network resources. The reason is that these correlations present a packing effect in wavelength and timeslot assignment, and tend to leave more free wavelengths and timeslots for further coming connection requests. The investigation suggests that the blocking performance can be improved by making a proper use of link-load correlation in ring networks.

4.3 Heuristic algorithms for multi-fiber networks

Although some single-fiber metro networks exist, the most popular metro networks utilize multiple fibers in network links. In this section, some heuristic approaches are presented to improve blocking performance by increasing the packing function in fiber, wavelength and timeslot assignment schemes in multi-fiber ring networks, where every two adjacent nodes are connected by F fibers in each direction.

In multi-fiber cases, to accommodate a dynamic connection request, the routing, fiber, wavelength and timeslot assignment problem must be solved. Similar to single-fiber cases, the problem is decoupled into a routing subproblem and a fiber, wavelength and timeslot assignment (FWTA) subproblem. It is proposed here to solve the FWTA subproblem as a single compound problem in order to use only up to two end-to-end handshakings, and thus to take the maximum time of one round-trip delay to set up or reject a connection. Since traffic in agile all-optical networks is highly variable in time, in order to keep network control traffic in a reasonable level, the objective of this design is to use the minimum amount of network control traffic while maintaining network connection operation working efficiently.

Once decoupled, the DRWTA problem will be solved by working out the two subproblems step by step. For the routing subproblem, the shortest path routing is still the choice here to minimize network resource usage in multi-fiber cases. To achieve maximum utilization of multiple fibers, it is proposed to find a FWTA solution among a complete set of information on the utilization of fibers/wavelengths/timeslots.

The performance of the algorithms proposed in this section will be evaluated via simulation with the traffic model detailed in Chapter 3. All the figures in this section show the average network blocking probability for 100 replications with 1 million random requests each for ring networks with $N=16$, $F=4$, $W=8$ and $T=8$.

4.3.1 A fiber designation scheme

In [Barr96], it has been shown that the performance benefit of wavelength conversion in ring networks is relatively small, and it drops dramatically with the increase in number of fibers. In Section 4.2, it has also been shown that network blocking performance will improve when the link-load correlation is used as a packing mechanism in assignment schemes in ring networks. Therefore, the design consideration here is to incorporate the above results in fiber designation schemes: increasing link-load correlation during the fiber assignment stage for each connection request in ring networks in order to decrease network blocking.

To introduce packing effects into fiber assignment algorithms by making use of link-load correlation, the proposed fiber designation scheme here has two steps. First of all, create indices for the fibers on each hop link of the ring networks so that fibers are numbered from 1 to F in each hop link. Then, during the fiber assignment stage, assign fibers with the same index number in hop links along the routing path of a request to traffic that belongs to the particular request. In this way, each lightpath is set up in fibers having the same index number in different links along its routing path, and thus traffic accommodation in adjacent links is better correlated. This fiber designation scheme bundles fibers together with their wavelengths, and distinguishes one wavelength from others by using both fiber and wavelength indices. In other words, it is proposed to introduce fiber continuity constraint in the fiber assignment stage to pack traffic in order to reduce network blocking. This fiber designation scheme is named "indexed fiber designation scheme."

The performance of the proposed fiber designation scheme is evaluated through simulation. Fig. 4.6 shows the simulation result of blocking probability versus network load for the indexed fiber designation scheme and a random fiber designation scheme, which randomly selects a fiber that has enough bandwidth for the current connection request on each hop link along the routing path of the current connection request. To make a fair comparison, both methods are followed by random fiber, wavelength and timeslot assignment. Shortest path routing is used in both curves. It is evident that the indexed fiber designation scheme has greatly improved blocking performance and therefore significantly outperforms the random fiber designation scheme in the entire range of network loads. The indexed fiber designation scheme in fact utilizes the proposed fiber continuity constraint, with the intrinsic wavelength continuity constraint and slotting constraint in WDM-TDM all-optical networks, to pack network traffic together and consequently achieves better performance. The sizes of the 95% confidence intervals of the simulation results are decreased from ±1% of the results to ±0.2% of the results when traffic load increases from 30% of network capacity to 90% of network capacity.

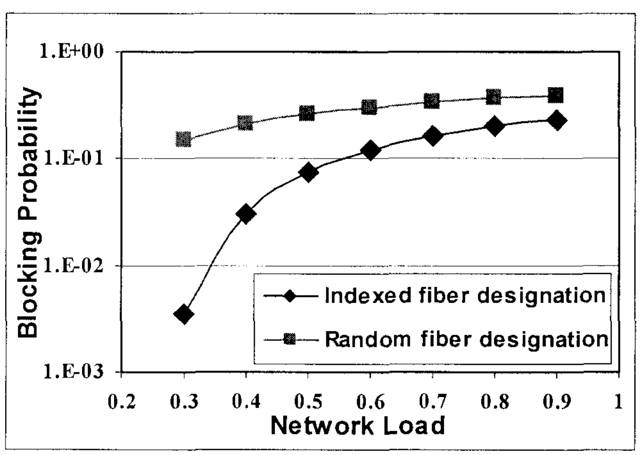


Fig. 4.6. Blocking probability of indexed fiber designation compared to random fiber assignment.

4.3.2 Fiber, wavelength and timeslot assignment schemes

To properly express the highly dynamic traffic in agile all-optical networks, this thesis adopts the traffic model where lightpath requests arrive or depart one at a time following some statistical distributions. In the literature, approaches of wavelength assignment with this model are focused on minimizing blocking probability for a given network. The

Random, First-Fit, Least-Used and Most-Used are commonly used heuristic approaches for dynamic wavelength assignment problems, which work for both single fiber and multi-fiber networks [Zang00]. In this section, the four heuristic approaches are discussed and may be modified in solving the dynamic fiber, wavelength and timeslot assignment problems in multi-fiber agile all-optical metro ring networks. To solve the DRWTA problem for dynamic requests, a combination of four heuristics for fiber assignment and four heuristics for wavelength assignment will be investigated here based on the indexed fiber designation scheme proposed in Section 4.3.1, which is specially designed for the multi-fiber cases to improve network blocking performance.

The design of fiber, wavelength and timeslot assignment schemes is highly affected by the design of the network control system. In this thesis, agile all-optical networks are distributed-controlled metro networks with ring topologies. In distributed-controlled networks, there are two kinds of link-state information control schemes based on whether global link-state information is available at each network node. To make global link-state information available at each network node, link-state information exchange should be deployed between network nodes. This, in turn, will result in extensive control traffic between network nodes. When network traffic is highly dynamic, this information exchange will cause significantly heavy control traffic load in networks. Therefore, the fiber, wavelength and timeslot assignment schemes designed here only utilize local link-state information in the connection setup.

With only local link-state information, some heuristics for wavelength assignment do not work. In literature, the Least-Used and Most-Used algorithms need global link-state information in order to determine the wavelength that is least-used or most-used in a network. With the design of no global link-state information exchange in a network control system, these two algorithms need to be modified in order to be feasible for fiber or wavelength assignment based on local link-state information. Local link-state information indicates the states of links on the shortest path of a connection request, which is collected during the call setup signaling. Here, the concepts of the least-used fiber/wavelength on shortest path and the most-used fiber/wavelength on shortest path are introduced. The least-used fiber/wavelength on shortest path is the fiber/wavelength that has the biggest number of idle timeslots in common in all links along the shortest path of a connection request. Likewise, the most-used fiber/wavelength on the shortest path is the fiber/wavelength that has the smallest number of idle timeslots in common in all links along the shortest path of a connection request. With these two definitions, the four algorithms are defined accordingly as follows:

- First-Fit: The algorithm attempts to route each dynamic request on the first available fiber/wavelength on the shortest path, where the available fiber or the available wavelength indicates the fiber or wavelength that has a sufficient number of idle timeslots in common in all links along the routing path of a connection request for the setup of the connection.
- Least-Used on shortest path: The algorithm tries to route each connection request in the least-used and available fiber/wavelength on the shortest path.
- Most-Used on shortest path: The algorithm seeks to route each connection request in the most-used but available fiber/wavelength on the shortest path.
- Random: The algorithm randomly routes each connection request to any available fiber/wavelength on the shortest path.

The first algorithm aims to pack fibers/wavelengths according to a fixed order. The second algorithm attempts to spread dynamic traffic among all fibers/wavelengths. The third algorithm tries to pack fibers/wavelengths according to their utilization and the fourth algorithm distributes dynamic traffic randomly so that the average fiber/wavelength utilizations are balanced. The fiber, wavelength and timeslot assignment schemes that will be investigated in this section are the combinations of each of the four possible fiber assignment algorithms alongside each of the four possible wavelength assignment algorithms, creating 16 fiber and wavelength assignment combined algorithms.

After the fiber and wavelength assignments, the next step is timeslot assignment. In literature, packed algorithms have been shown to always outperform random algorithms and spread algorithms [Zang00]. There are two packed algorithms in literature: First-Fit and Most-Used. The Most-Used algorithm slightly outperforms First-Fit algorithm. However, the original Most-Used algorithm calculates the most-used timeslots in the network from the information of global link states, which is not available in the designed networks in this section. In addition, the concept of the most-used timeslots on the shortest path is useless in timeslot assignment scheme because the most-used timeslots on the shortest path are the busy timeslots along the shortest path that cannot be reused to accommodate new connections. For these reasons, First-Fit algorithm is chosen to be the timeslot assignment algorithm here.

Simulation is deployed here to evaluate the performance of the 16 fiber, wavelength and timeslot assignment algorithms. The sizes of the 95% confidence intervals of the simulation results shown in the figures in this section are decreased from ±6% of the results when traffic load is 30% of network capacity, to ±1.5% of the results when traffic load is 40% of network capacity, and then to ±0.16% of the results when traffic load increases to 90% of network capacity.

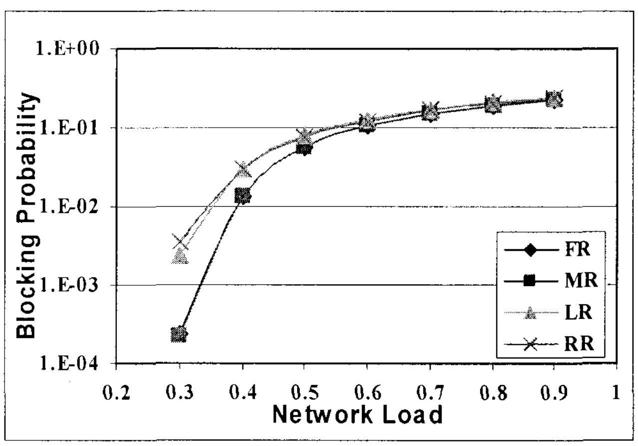


Fig. 4.7. Blocking probability of fiber assignment schemes, all followed by random wavelength assignment.

The simulation result shown in Fig. 4.7 compares the blocking performance of the four fiber assignment algorithms. To make a fair comparison, all methods are followed by Random wavelength assignment (R). The Random fiber assignment and Random wavelength assignment algorithm (RR) demonstrates close performance to the Least-Used fiber assignment and Random wavelength assignment algorithm (LR), while the

First-Fit fiber assignment and Random wavelength assignment algorithm (FR) presents a similar performance to the Most-Used fiber assignment and Random wavelength assignment algorithm (MR). However, FR and MR result in a large reduction in the blocking probability compared to LR and RR when network traffic load goes from light to medium, and enjoy a slightly better performance than LR and RR when networks are heavily loaded. This shows that the packed fiber assignment algorithms achieve a much better performance than spread and random algorithms, because packed algorithms increase load correlation between network links.

Moreover, Fig. 4.7 also shows that FR or RR slightly outperforms MR or LR when network load is medium to high, and most of the call blockings are caused by insufficient bandwidth. However, they underperform MR or LR when network load is light, and most of the call blockings are caused by the limitation of the wavelength continuity constraint and the slotting constraint.

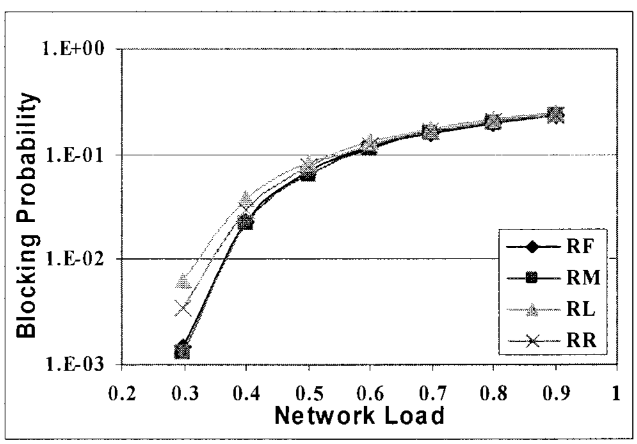


Fig. 4.8. Blocking probability of wavelength assignment schemes, all preceded by random fiber assignment.

Fig. 4.8 compares the network blocking probability of the four wavelength assignment algorithms, all preceded by Random fiber assignment. Of the four algorithms, the best performance is obtained again by packed algorithms, with the Random fiber assignment and Most-Used wavelength assignment algorithm (RM) having the lowest blocking probability, followed closely by the Random fiber assignment and First-Fit wavelength assignment algorithm (RF). The worst performance corresponds to the Random fiber assignment and Least-Used wavelength assignment algorithm (RL).

Now, the performance of packed algorithms for fiber and wavelength assignment is compared by investigating the four combinations of these algorithms: First-Fit fiber assignment and First-Fit wavelength assignment (FF), First-Fit fiber assignment and Most-Used wavelength assignment (FM), Most-Used fiber assignment and First-Fit wavelength assignment (MF) and Most-Used fiber assignment and Most-Used wavelength assignment (MM).

Table 4.7 Blocking probability of the combination algorithms of packed assignment schemes

Network Load	FF	FM	MF	MM
0.30	1.719E-04	1.396E-04	1.583E-04	1.240E-04
0.40	1.150E-02	1.053E-02	1.117E-02	1.030E-02
0.50	5.251E-02	5.041E-02	5.262E-02	5.091E-02
0.60	1.019E-01	9.971E-02	1.023E-01	1.005E-01
0.70	1.474E-01	1.456E-01	1.480E-01	1.461E-01
0.80	1.867E-01	1.847E-01	1.873E-01	1.860E-01
0.90	2.204E-01	2.188E-01	2.220E-01	2.205E-01

Simulation results show (Table 4.7) that the performance of the four combinations is very similar, a prediction that can be made using Fig. 4.7 and Fig. 4.8. The Most-Used scheme is the best wavelength assignment algorithm among the four algorithms. For fiber assignment, Most-Used (which packs fibers according to their utilization) is the best algorithm when network load is light, while First-Fit (which tries to pack fibers according to a fix order) is the best algorithm when network load is 50% or higher. This is because the network traffic is more evenly distributed among fibers for higher loads. The difference in fiber utilization decreases while network load increases. Therefore, Most-Used becomes less efficient for packing than the First-Fit scheme.

In conclusion, a systematic study of the possible combinations of algorithms has been performed, resulting in the assertion that packed algorithms reduce blocking probability, especially the combination of Most-Used fiber assignment with Most-Used wavelength assignment, and the combination of First-Fit fiber assignment with Most-Used wavelength assignment. Moreover, simulation results show that with the indexed fiber designation scheme, the performance of the packed algorithms makes a significant improvement compared to the scheme of random fiber/wavelength/timeslot assignment along the shortest path. The algorithms proposed in this section utilize local link-state information to avoid overloading of the network control channel for highly dynamic traffic accommodation. Based on the network and traffic model defined in Chapter 3 and the algorithms proposed in this section, a connection will travel approximately $N/4$ hops in average. With F fibers in each direction of a hop link, W wavelengths per fiber and T timeslots per frame, the number of timeslot states per hop link is FWT. With indexed fiber designation scheme, in average, the proposed heuristic approaches combine the FWT number of timeslot states of $N/4$ hop links on the routing path of a connection request and check the availability of FWT number of timeslots on the routing path to set up the connection. In addition, First-Fit algorithm utilizes first available fiber/wavelength/timeslot. Thus, the heuristic approaches including First-Fit algorithm do not need to check the states of all FWT number of timeslots to make a decision. Therefore, the heuristic approaches here can be solved in polynomial time. An asymptotic estimate of the complexity of the algorithm is $O(NFWT\log(FWT))$, which is sufficiently fast enough to serve highly dynamic connection requests in agile all-optical networks.

4.4 Least-Loaded algorithms for multi-fiber networks

The indexed fiber designation scheme proposed in Section 4.3 introduces fiber continuity constraint in DRWTA algorithms, which intends to pack traffic in order to decrease network blocking. However, this design removes the flexibility of fiber assignment. Therefore, in some cases, blocking may be caused by this limitation. There is possibility that a connection can be set up if the fiber assignment is not limited to the same index.

For a certain connection request, exhaust fiber, wavelength and timeslot assignment search is a way to avoid fiber continuity constraint caused blocking. This means all the possible fiber assignment combinations for all hop links on the routing path of the connection request are attempted. For example, a 16 node ring network has 4 fibers in each direction of each hop link, 8 wavelengths per fiber and 8 timeslots per frame. A connection travels 4 hops in average, and then the fiber assignment through exhaust search has $4^4 = 1024$ combinations. An exhaust fiber, wavelength and timeslots assignment search needs to check the availability of $1024 \times 8 \times 8 = 65,536$ number of timeslots on the routing path to set up the connection, an extensive amount of calculation for one connection request. For the same network setting, the heuristic approaches proposed in Section 4.3 only need to check the availability of $4 \times 8 \times 8 = 256$ number of timeslots on the routing path to set up a connection. Thus, the exhaust fiber, wavelength and timeslot search approach is not appropriate to be a fiber, wavelength and timeslot assignment algorithm for the real time traffic operation in agile all-optical networks holding fast changing traffic.

In literature, the Least-Loaded (LL) heuristic algorithm is widely accepted as the best wavelength assignment scheme for dynamic request accommodation in multi-fiber networks. This heuristic assigns fiber and wavelength to a connection request in the order of wavelength first and fiber second [Kara98]. It firstly selects the minimum index wavelength that has the largest residual capacity on the most loaded hop link along the routing path of a connection request, and then chooses the first fiber that has the selected wavelength available in the fiber. Therefore, the LL rule reduces to First-Fit wavelength assignment when it is applied into single-fiber networks. In addition, the LL heuristic algorithm uses only local link-state information and is thus of the interest to this thesis. In this section, LL rule is investigated for the fiber, wavelength and timeslot assignment in WDM-TDM all-optical metro ring networks.

The fiber, wavelength and timeslot assignment (FWTA) problem in multi-fiber WDM-TDM all-optical networks differs from the fiber and wavelength assignment (FWA) problem in multi-fiber WDM networks in two aspects. First of all, the FWTA has an additional level of assignment (timeslot assignment). Secondly, the assignment in the timeslot level has an additional constraint (slotting constraint).

On the other hand, the LL rule is designed for the fiber assignment problem in multi-fiber WDM networks because the fiber assignment does not have the continuity constraint. Therefore, the LL rule can only be applied in the fiber assignment level of the fiber, wavelength and timeslot assignment problem in multi-fiber WDM-TDM all-optical network because in the problem, wavelength assignment has the wavelength continuity constraint, and timeslot assignment has the slotting constraint. Additionally, the problem of wavelength and timeslot assignment (WTA) in single-fiber WDM-TDM networks, which has two levels of assignments, looks similar to the FWA problem in multi-fiber WDM networks, which also has two levels of assignments. However, the LL rule in solving the FWA problem in multi-fiber WDM networks is not applicable to the WTA problem in single-fiber WDM-TDM networks because of the wavelength continuity constraint in wavelength assignment.

There are three questions to answer while applying the LL rule into the FWTA algorithms. The first question is how to order the three levels of assignments. The second question is how to adjust the LL rule to fit it into FWTA algorithms. The last question is what the timeslot assignment algorithm is, since LL rule only determines the fiber and wavelength assignments.

To the first question, the LL algorithm defined here for FWTA determines wavelength first, fiber second and timeslots last for the setup of each connection. Since packed algorithms have better performance, explained in Section 4.3, First-fit heuristic is adopted as the timeslot assignment algorithm, the answer to the third question. To the second question, it is noticed that the residual capacity of a wavelength in different fibers may differ from each other in multi-fiber WDM-TDM networks. This is the key point that disagrees with the situation in multi-fiber WDM networks. This, in turn, makes the fiber assignment in FWTA algorithm distinct from the fiber assignment in WTA algorithm. Two FWTA algorithms are therefore defined through applying LL rules.

- LL with First-Fit: First of all, the algorithm selects the minimum index wavelength that has the largest total residual capacity on the most loaded hop link along the routing path of a connection request. Secondly, the algorithm chooses the First-Fit fiber in each hop link that the selected wavelength has sufficient capacity for the connection setup. Thirdly, the algorithm finds the idle timeslots in common for all hop links on the routing path of the connection request and then assigns timeslots for the connection request according to the First-Fit rule.
- LL with Least-Used: First of all, the algorithm selects the minimum index wavelength that has the largest total residual capacity on the most loaded hop link along the routing path of a connection request. Secondly, the algorithm chooses a fiber in each hop link that the selected wavelength has the largest residual capacity (Least-Used rule) among all fibers in the link. Thirdly, the algorithm finds the idle timeslots in common for all hop links on the routing path of the connection request and then assigns timeslots for the connection request according to the First-Fit rule.

The first algorithm chooses the First-Fit fiber in each hop link while the second algorithm selects the Least-Used fiber for the selected wavelength in each hop link. The algorithm of LL with Least-Used tries to maximize the possibility of the successful connection setup for the current connection request by choosing the Least-Used fiber for the selected wavelength in each hop link. The performance of the two algorithms is evaluated through simulation. All the figures in this section show the average network blocking probability for 100 replications with 1 million random requests each for ring networks with $N=16$, $F=4$, $W=8$ and $T=8$.

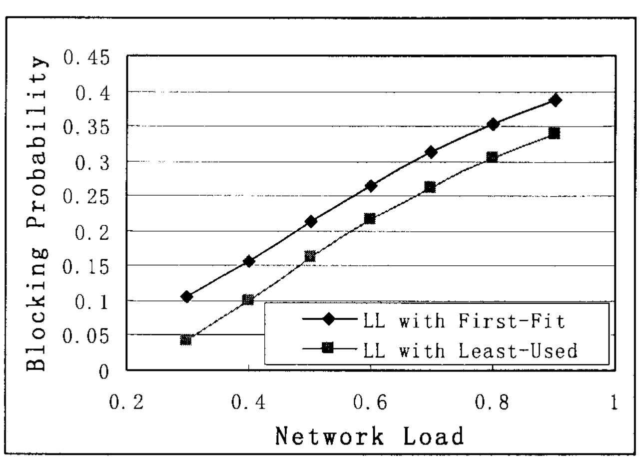


Fig. 4.9. Blocking probability of Least-Loaded algorithms.

Fig. 4.9 shows the blocking probability versus network load of the two algorithms with the blocking probability axis in linear scale. LL with Least-Used performs better than LL with First-Fit, which is expected with the design analysis of the algorithms. Fig. 4.10 compares the blocking probability of the Least-Loaded algorithms with the results in Section 4.3.1 with the blocking probability axis in logarithmic scale. It shows that the LL algorithms demonstrate better performance than the Random fiber designation algorithm, which means the fiber assignment in LL algorithms works better than random fiber pick up in each hop link. However, the performances of the two LL algorithms are much worse that the algorithm of the indexed fiber designation scheme with random fiber, wavelength and timeslot assignment, proposed in Section 4.3.1, especially when networks are light loaded and blockings are mainly caused by the wavelength continuity constraint and the slotting constraint.

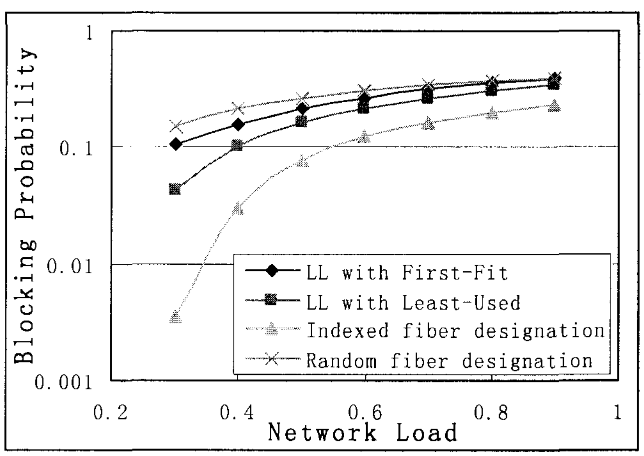


Fig. 4.10. Comparison of blocking probability of Least-Loaded algorithms and previous algorithms.

In both LL algorithms, sufficient idle capacity for a connection request is guaranteed in each hop link on the routing path of the connection through the selection of the wavelength and the fiber for the connection. However, the choices do not guarantee the connection setup because of the slotting constraint in timeslot assignment. This intrinsic characteristic of the LL algorithms cannot properly solve the problems of flexible bandwidth and slotting constraint introduced by the additional level of assignment, timeslot assignment. Therefore, the two LL algorithms are not as efficient as they are in solving the FWA problems in WDM networks. In addition, the bottleneck link selection mechanism in LL algorithms does not work as effective as it does in mesh networks such that the fiber assignment realized by LL heuristic does not achieve good blocking performance.

4.5 Concluding remarks

In this chapter, a distributed-controlled dynamic bandwidth allocation algorithm has been presented for single-fiber agile all-optical metro ring networks to accommodate dynamic and flexible bandwidth on demand, with the knowledge of global link-state information. Compared with the random wavelength and timeslot assignment algorithm (Random algorithm), and the First-Fit wavelength and timeslot assignment algorithm (First-Fit), the proposed algorithm requires a little more calculation. However, this algorithm outperforms the Random algorithm significantly and the First-Fit algorithm slightly because it considers the characteristics of ring networks and incorporates the dynamic programming technique. The blocking performance has been evaluated via simulation.

Although simulation is an essential tool in network design, it costs more time, effort and money than the tool of mathematical modeling. A quasi-analytical model has therefore been proposed here to facilitate the derivation of call blocking probability for single-fiber metro ring networks based on the random bandwidth allocation algorithm. The accuracy of the quasi-analytical model has also been verified via simulation. The model can be extended to multi-fiber networks when the indexed fiber designation scheme is integrated with shortest path routing and random wavelength and timeslot assignment to improve call blocking performance, because the indexed fiber designation scheme makes the bandwidth allocation for multi-fiber networks to be similar to single-fiber networks.

In multi-fiber ring networks, the proposed indexed fiber designation scheme introduces an additional limitation, fiber continuity constraint, into the FWTA problem in order to increase link-load correlation in traffic accommodation in ring networks according to a result derived in this chapter, reducing blocking by increasing link-load correlation. The benefit that comes from the indexed fiber designation scheme outweighs the limitation it introduces in network blocking. When it works together with the packing heuristics in FWTA, the best blocking performance is achieved by closely packing existing traffic together in fiber, wavelength and timeslot space, and leaving more global idle capacity for further incoming connection requests. Comparatively, the FWTA algorithms applying the LL rule do not work well because of the flexible bandwidth requirement and slotting constraint in the additional level of assignment, timeslot assignment, and the characteristic of ring network topology.

In short, this chapter has studied the bandwidth allocation algorithms and evaluated their blocking performances through both mathematical modeling and the simulation tool.

Ch. 5 Signaling and Reservation

In WDM-TDM agile all-optical networks, traffic is fast changing and has flexible bandwidth requirements. To accommodate traffic with diverse characteristics and quality-of-service (QoS) requirements into networks with the bandwidth allocation algorithm proposed in the previous chapter, an intelligent control mechanism is required to handle the sharing of link bandwidths and processing resources for network traffic. The intelligent control mechanism taking care of network connection operation and maintenance is known as signaling and reservation protocols. In this chapter, two kinds of control protocols are proposed and compared based on whether or not global link-state information is available.

Link-state based distributed routing has been widely accepted as an efficient routing algorithm. In networks where complete network link-state information is available in each node, link-state based distributed lightpath establishment is characterized by shorter stabilizing delays and lower blocking probability under light traffic load [Zang01]. Therefore, link-state based distributed routing, wavelength and timeslot assignment (RWTA) is chosen here to be the fundamental algorithm grounded on which signaling and reservation protocols is designed for agile all-optical metro networks. Based on whether or not complete network link-state information is available on each network node, signaling and reservation control protocols are categorized as control protocols with global information and control protocols without global information.

While maintaining a global link-state database, link-state information is usually not being exchanged instantly for two reasons [Zang01], [Shai01], and [Shen06]. First of all, the instant link-state information exchange results in an extensive amount of protocol overhead and thus may overload control channels in networks where traffic is highly dynamic. Additionally, for distributed-controlled networks designed here, the time may be considerable to update network link states and to have global link-state databases converge. Thus, instant link-state information update may cause link-state databases to be unstable in networks where connection establishment or removal takes place frequently.

For these reasons, two alternative principles are proposed in the literature to make a tradeoff between the accuracy of link-state databases and the amount of protocol overhead: periodic link-state update and triggered link-state update [Shai01]. In this thesis, two control protocols, which control the global link-state information update and the connection operation to serve a variety of QoS network traffic, are presented based on the two link-state update principles: periodic link-state update protocol and triggered link-state update protocol. In metro all-optical networks where traffic is highly dynamic, it is notable that some kinds of delays, such as propagation delay (tens to hundreds of microseconds) and link-state information update delay, may be considerable compared with the arrivals and departures of connection requests while either of these two control protocols applies.

In the case where no global link-state information is collected, a control protocol, which divides the process of connection setup into two stages, is designed here for agile all-optical metro networks. The information of available network resources is gathered during the first stage of connection setup through signaling. Bandwidth allocation for different QoS network traffic, the second stage of connection setup, is then implemented based on the collected link-state information through the dynamic RWTA calculation, signaling and network resource reservation. In this case, delay exists in both stages of the process of connection setup because of the intrinsic characteristic of networks: propagation delay.

Consequently, for the control protocols with or without global link-state information awareness, it is possible that the link-state information obtained at the stage of the connections setup is out-of-date because of the delays in the two kinds of control protocols. This, in turn, may result in incorrect dynamic RWTA decisions. Thus, the delays may reduce the networks' ability to accommodate connection requests that are highly variable in time. Therefore, the impact of the delay, which cause stale link-state information on the blocking performance of bandwidth allocation schemes is further investigated in the design of signaling and reservation protocols.

5.1 Control protocols with global information

This section studies the signaling and reservation protocols to control network dynamics in directing traffic at the connection level and to update network link-state information in accordance to connection operations. Here, in agile all-optical metro networks that have global link-state information available, the establishment and removal of each connection is handled with both signaling and reservation mechanisms while the link-state update is controlled through signaling mechanism only. Two control protocols are presented here: periodic link-state update protocol and triggered link-state update protocol. The performances of the two protocols are compared through simulation.

The objective in the design of link-state update protocols in this thesis is to minimize the protocol overhead while maintaining the accuracy of the link-state database of a network at a certain level. The protocol overhead has two aspects: the content of link-state information, which determines how much information to be exchanged, and the rate of link-state update, which decides the frequency of link-state information exchange.

Adopting the concepts from [LiYa02], the content of link-state information in agile all-optical metro networks is classified into two kinds here: quasi-static information and dynamic information. Quasi-static information, which usually remains constant over a long duration and does not vary with the change of connection status in networks at any time, includes network topology information, optical impairment parameters and signal qualities of each link, the number of fibers per link, the number of wavelengths per fiber and the number of timeslots per frame, etc. In contrast, dynamic information, *denoted specifically as link-state information in the following part of this chapter*, is represented by fiber, wavelength and timeslot availability at each link that changes in response to the dynamic connection operations in networks. In order to avoid unnecessary information exchange in the distributed-controlled networks, quasi-static information is manually provisioned into the network configuration and is not refreshed unless the lower level channel quality surveillance mechanism indicates an emergency in network link availability status. Here, only link-state information is updated frequently to reflect dynamic connection operations with the control of either periodic link-state update protocol or triggered link-state update protocol.

In these signaling and reservation control protocols, the rate of link-state update determines the staleness of network link states. There are two potentials to bring about network conditions of out-of-date link states, which may influence network blocking performance. The first source of stale link states origins from network propagation delay. The link states may become outdated during the process of network resource reservation for connection setup because of network propagation delay. The second cause of out-of-date link states is the delay in the link-state update signaling. The link-state update is refreshed periodically or is triggered by some thresholds rather than being updated instantly. Based on either of the two control protocols, the intervals between any two adjacent link-state updates are usually much longer than the propagation delays along any routes of network connections. Thus, the second cause is the primary source of stale link-state information. Therefore, network propagation delay is ignored in the design of the two link-state update protocols. The blocking probability of DRWTA algorithms with the consideration of the protocol-caused outdated global link-state information is investigated for QoS traffic accommodation in agile all-optical networks.

5.1.1 Periodic link-state update protocol

Periodic link-state update protocol includes two parts: *periodic link-state signaling*, and *connection operation*. In periodic link-state signaling, link-state update messages provide a refresh of the fiber, wavelength and timeslot availability of each link in a network with a constant refresh period. The nature of periodic link-state update makes the protocol overhead on processor and bandwidth resources for the exchange of link-state information to be predictable. In connection operation, bandwidth allocation decision for each QoS connection request is calculated on a source node based on the global link-state database. The bandwidth allocation command for each request is signaled to reserve necessary network resources along the routing path of each connection.

To simplify the analysis, agile all-optical metro networks are modeled as single fiber ring networks. It is straightforward to extend to multiple fiber cases. As it is solved in the previous chapter, the dynamic RWTA problem is decoupled into a routing subproblem and a wavelength and timeslot assignment (WTA) subproblem. The routing subproblem is solved by the shortest path routing algorithm. For the WTA subproblem, to simplify the analysis of the control protocol and the impacts of so caused delays, two algorithms are used and their blocking performances are compared here: the First-Fit wavelength assignment and First-Fit timeslot assignment scheme (FF) and the random wavelength assignment and random timeslot assignment scheme (RR).

Periodic link-state signaling: In a network applying periodic link-state update protocol, each node keeps accurate wavelength and timeslot availability information for its own outgoing links and potentially stale wavelength and timeslot availability information for the other links in the network. The link-state changes in accordance to connection operations are saved in operating nodes only. Link-state updates are exchanged among the network nodes with a constant update rate. Upon the receiving of link-state updates, each node refreshes its database accordingly. Control message processing delays are neglected in the design analysis as they are much smaller than the link-state update interval. Since metro all-optical networks usually span tens of kilometers per hop, the propagation delay in metro networks is usually within milliseconds. On the other hand, the inter-arrival time of bandwidth requests ranges from seconds to minutes; the link-state update interval, which normally takes a time period comparable to the inter-arrival time, is therefore much longer than the network propagation delay. Therefore, the protocol design here focuses on the research of the impact of stale information caused by the periodic link-state updates.

Connection operation: Connection operation includes *connection establishment* and *connection removal*. Connection establishment includes dynamic RWTA calculation, and signaling and bandwidth allocation while connection removal includes signaling and network resource release. The propagation delay along the routing path of each connection and the processing delay in RWTA calculation, signal and reservation for each connection are ignored for the same reason.

Connection establishment: The scheme of source node RWTA calculation and hop-by-hop forward reservation is adopted here for signaling and reservation in connection setup. It is assumed that there are always enough resources in the customer access links of the network. On the arrival of a new connection request, dynamic RWTA calculation takes place on the source node of the connection based on the global link-state database in the node. When the dynamic RWTA calculation fails to find sufficient network resources for the setup of the connection, the source node rejects the connection for the reason of insufficient network resources without trying to signal the connection through the network. In fact, some *RWTA failures* may be due to the stale link-state information in the source node because of the delay in the update of network link states while other *RWTA failures* are truly caused by insufficient network resources.

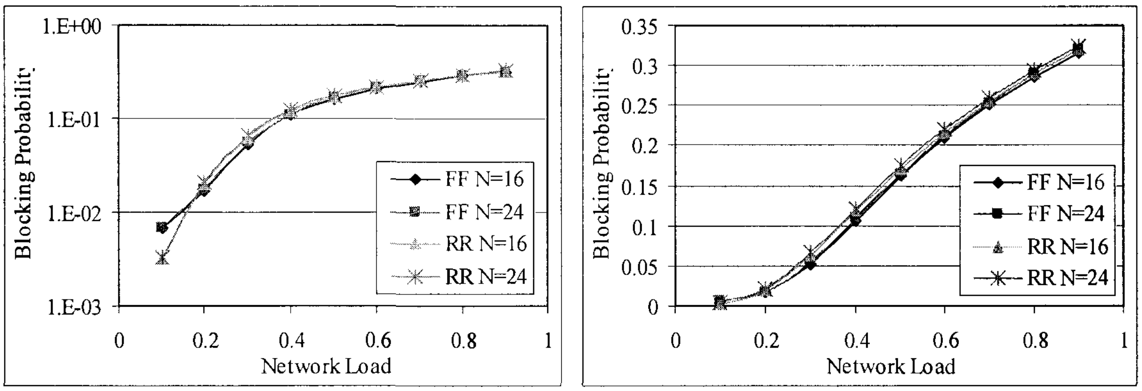
When the dynamic RWTA calculation successfully finds a solution for the setup of the connection with the decision of a wavelength and its timeslots, the source node initiates a hop-by-hop reservation process through signaling to reserve the requested timeslots on the wavelength in each link on the routing path of the connection. As the signaling message passes along the routing path of the connection, each node on the path performs an admission test to check the availability of requested resources in its outgoing link. If the requested resources are idle, the switch reserves the bandwidth on behalf of the new connection before forwarding the reservation request to the node on the next hop of the routing path. Once the requested wavelength and timeslots are reserved in all links along the routing path, the destination node of the connection generates an approval notice and sends it back hop-by-hop to the source node, indicating the admission of the connection and committing the timeslots on the wavelength in all links of the routing path to be dedicated to the connection for the duration of the connection.

A *setup failure* occurs if an admission test fails on any nodes along the routing path if some required timeslots on the requested wavelength are found busy in the outgoing link of the node doing the admission test. When a node on the routing path finds the unavailability of requested resources in its outgoing link, it generates a *setup failure* notice and send it back hop-by-hop towards the source node of the connection. On reception of the signaling message, each node upstream along the routing path releases the resources reserved on behalf of the new connection in its outgoing link before forwarding the notice back to the node on the previous hop of the routing path. Once all network resources dedicated to the new connection are released, the source node rejects the connection for the reason of *setup failure*. The blockings caused by *setup failures* consume considerable processing resources in networks in the progress of signaling and reservation. In addition, a connection blocked by a *setup failure* temporarily holds resources at the upstream links, which may result in additional *setup failure*s for other connections in interim. Therefore, the blockings caused by *setup failures* are much more expensive than the blockings caused by *RWTA failures*.

Connection removal: On the arrival of a clear request of an existing connection, the source node initiates a resource release request. While this signaling message goes towards the destination node along the routing path of the connection, each node on route forwards the signaling message to the node on the next hop along the routing path not until it releases resources reserved for the connection in its outgoing link. Once all network resources dedicated to the connection are released, the destination node generates a release confirmation notice directing to the source node to confirm the removal of the connection.

5.1.2 Simulations for periodic update protocol

Here, agile all-optical metro networks are modeled as single fiber ring networks. By applying the periodic link-state update protocol, the blocking performances of dynamic RWTA algorithms of the Random wavelength and timeslot assignment (RR) and the First-Fit wavelength and timeslot assignment (FF) are compared for 16-node ring and 24-node ring networks under different periodic update intervals. It is assumed that $W=8$ and $T=8$. The mean connection holding time is normalized to $1/\mu=1$ second. Different network traffic loads are modeled by varying the mean inter-arrival time between bandwidth requests. Blocked connection requests are discarded. For Fig. 5.1 through Fig. 5.9, the sizes of the 95% confidence intervals of the simulation results are decreased from ±3% of the results to ±0.3% of the results when traffic load increases from 10% of network capacity to 90% of network capacity.

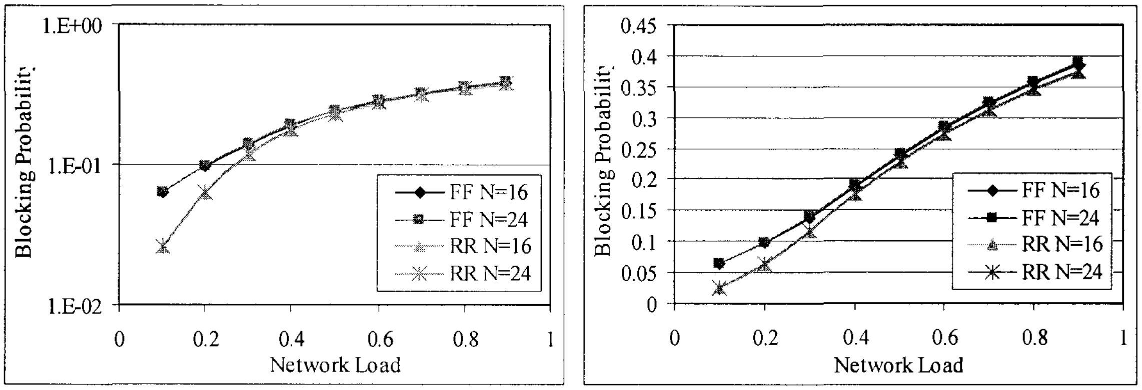


a) logarithmic scale b) linear scale

Fig. 5.1. Blocking probabilities of FF and RR algorithms for 16-node ring and 24-node ring, update period = 0.01.

The simulation result shown in Fig. 5.1 compares the blocking performance when update interval equals to 0.01 seconds. In this case, RR performs better than FF only when the traffic load is lower than ~18% of the network capacity. This is because FF tends to pack wavelengths/timeslots according to a fixed order. When traffic load is very light, the stale global information is more likely to cause FF to make incorrect routing, wavelength and timeslot assignment decisions than RR, which in turn may cause more blocking for FF than RR. When traffic load increases, the blocking of bandwidth requests becomes mainly caused by a lack of available timeslots on wavelengths. As FF performs much better than RR with up-to-date global information, which has been shown in Ch. 4, FF still wins in this case. Fig. 5.1 also shows that the number of nodes in a ring network does not have significant effects on the overall blocking probability, although a smaller number results in a slightly better blocking performance.

When the update period is 0.1 seconds, it is shown (Fig. 5.2) that RR outperforms FF in the whole range of network traffic load, which indicates that FF is more sensitive to the freshness of global information. When a network is lightly loaded, the blocking of RR is much lower than the blocking of FF. When network traffic load increases, the blocking probability of RR becomes similar to that of FF because most of the blocking in this condition is caused by a lack of network resources to accommodate bandwidth requests. Again, the number of nodes in a network has only a minor effect on network blocking.



a) logarithmic scale b) linear scale

Fig. 5.2. Blocking probabilities of FF and RR algorithms for 16-node ring and 24-node ring, update period = 0.1.

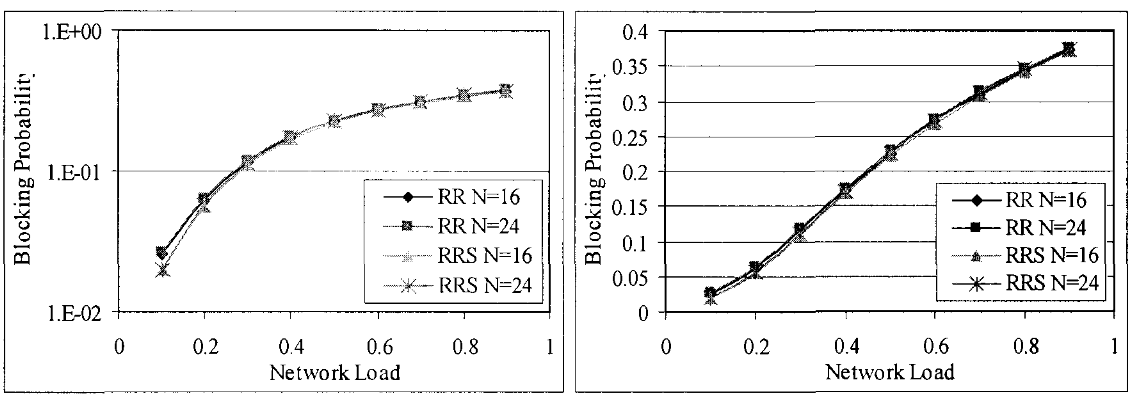


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Fig. 5.3. Blocking probabilities of RR and RRS algorithms for 16-node ring and 24-node ring, update period = 0.1.

Considering the characteristics of flexible bandwidth assignment, the random timeslot assignment scheme has two variations. One variation is when the wavelength and all the timeslots required for a bandwidth request are chosen randomly from the available ones, which is denoted as RR. The other variation combines the Random and the First-Fit scheme together: the wavelength and the first timeslot are selected randomly but the subsequent timeslots required to fulfill the bandwidth request are assigned from available timeslots on the wavelength in the order of timeslot index, which is denoted as RRS, random start point for timeslot searching. The later scheme makes the timeslot assignment in a more ordered form. Fig. 5.3 presents the blocking performance for a 16-node ring and a 24-node ring with an update interval of 0.1 seconds. RRS requires less calculation since only two numbers are computed randomly and performs marginally better than RR.

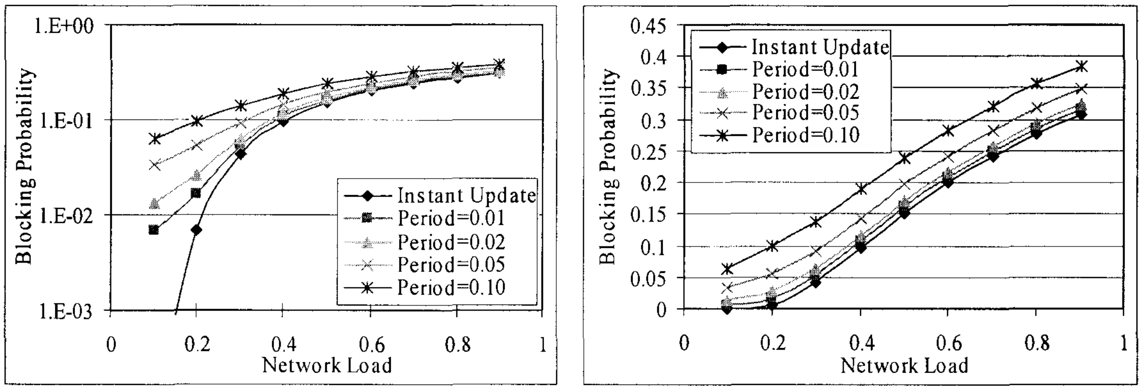

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Fig. 5.4. Comparison of blocking probabilities, FF algorithm, 16-node ring, different update periods.

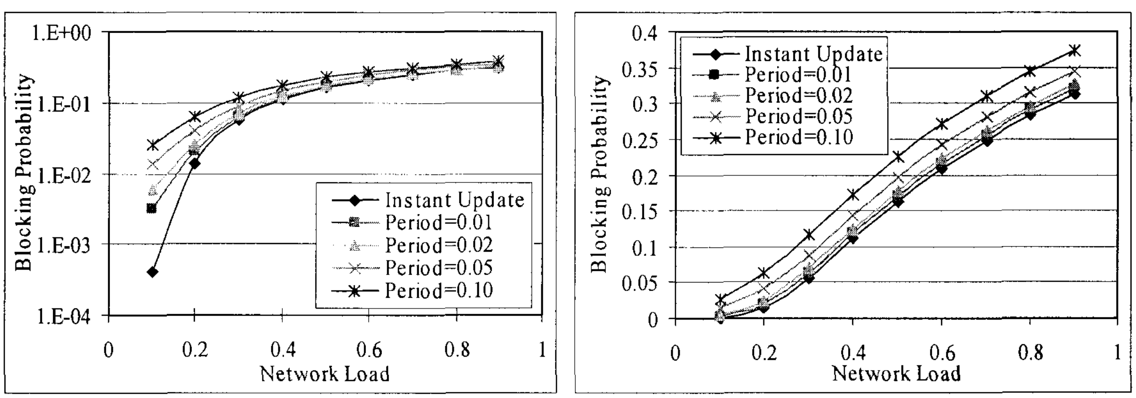

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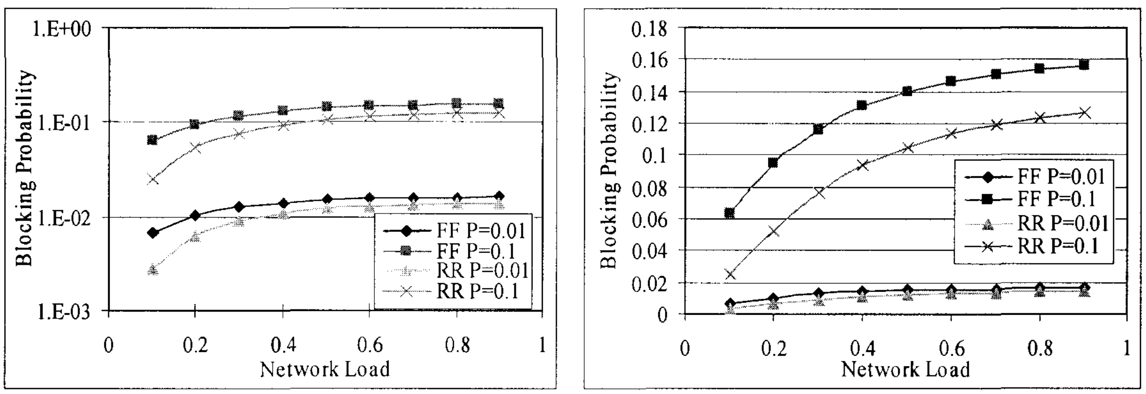
Fig. 5.5. Comparison of blocking probabilities, RR algorithm, 16-node ring, different update periods.

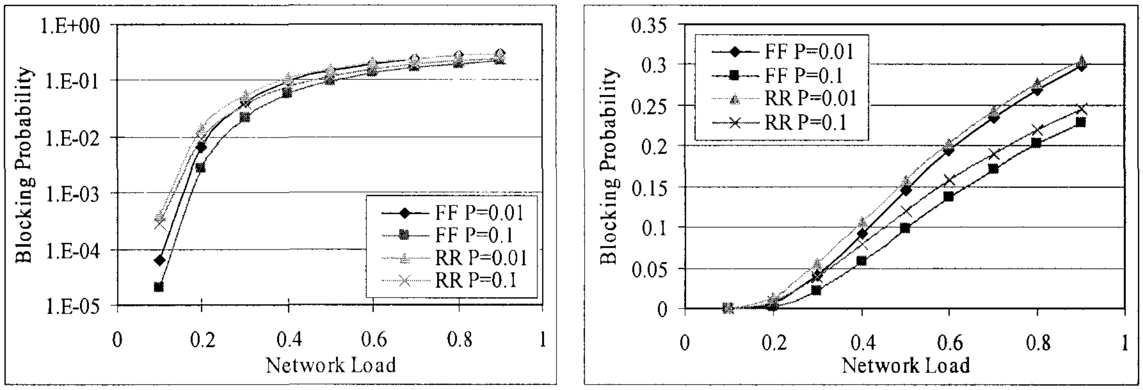
By varying the global information update period from 0, to 0.01, 0.02, 0.05 and 0.1, Fig. 5.4 and Fig. 5.5 compare the effects of different staleness of global information on the blocking performance of a 16-node ring network using the FF assignment scheme and RR assignment scheme separately. Being two components of total blocking, the blocking caused by *setup failures* and the blocking caused by *RWTA failures* are shown in Fig. 5.5 and Fig. 5.6 separately. The longer update period results in more incorrect global information, which is more likely to lead to inappropriate WTA assignments and hence more blockings. Although the lack of resources is the main reason of blocking under heavy traffic load, out-of-date global information still contributes a considerable part to total network blocking, which can be seen from the significant difference of blocking curves with different update intervals under heavy load. Determining the appropriate frequency of link-state updates involves a compromise between network capacity and control overhead.



a) logarithmic scale b) linear scale

Fig. 5.6. Probabilities of the blocking caused by setup failures with FF and RR algorithms for 16-node ring, update period = 0.01, 0.1.

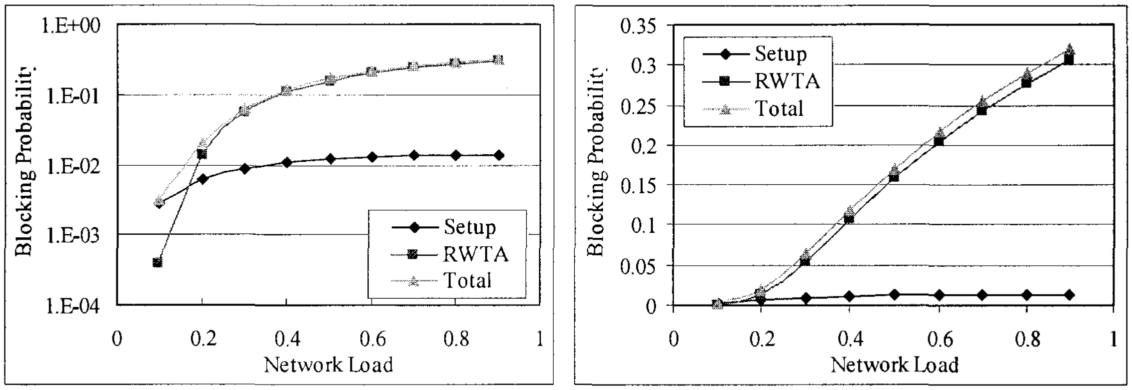
Fig. 5.6 shows the blockings caused by *setup failures* for FF and RR algorithms in 16-node ring networks when update period equals to 0.01 and 0.1. When update period equals to 0.01, the blocking caused by *setup failures* increases steadily from the range of some multiples of 0.001 to the range of some multiples of 0.01 with the increase of network load from 10% to 90% of network capacity for both FF and RR algorithms. When update period is 0.1, the blocking caused by *setup failures* increases from the range of some multiples of 0.01 to the values between 0.1 and 0.2 for both FF and RR algorithms. However, the *setup failure* loss when period = 0.1 is significant larger than the *setup failure* loss when period = 0.01 for both FF and RR algorithms. The four approximate parallel curves shown in Fig. 5.6 a) indicates that the ratio of blocking increase for both link-state update period settings and both dynamic RWTA algorithms are similar. Nevertheless, the real values of the loss increase in case of period = 0.1 when network load moves from 10% to 90% of network capacity is much bigger than the real values of the loss increase in case of period = 0.01 for both FF and RR algorithms, shown in Fig. 5.5 b). The RR algorithm considerably outperforms FF algorithm in this costly blocking as expected, especially in case of period = 0.1 because the FF algorithm is more sensitive to the stale link-state information.



a) logarithmic scale b) linear scale

Fig. 5.7. Probabilities of the blockings caused by RWTA failures with FF and RR algorithms for 16-node ring, update period = 0.01, 0.1.

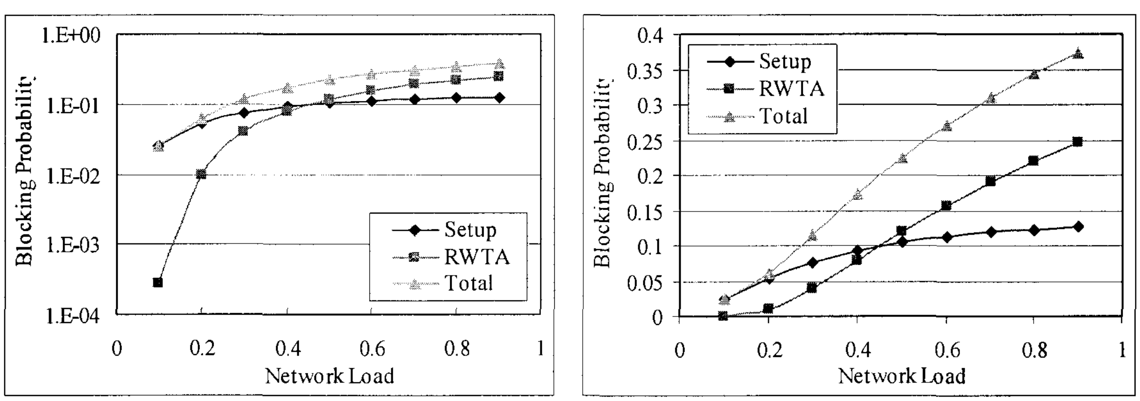
The probabilities of the blockings caused by *RWTA failures* with FF and RR algorithms in 16-node ring networks is shown in Fig. 5.7 for cases when the update period equals to 0.01 and 0.1. The sizes of the 95% confidence intervals of the simulation results are decreased from ±4.6% of the results to ±0.5% of the results when traffic load increases from 10% of network capacity to 90% of network capacity. Of the four curves, the best performance is achieved by FF algorithm in case of period = 0.1 while the worst performance corresponds to RR algorithm in case of period = 0.01. Their performance difference is significant when a network is heavily loaded. In between, FF algorithm in case of period = 0.01 performs better than RR algorithm in case of period = 0.1 when network load is 10% of network capacity, whereas their performances are in reverse order when network load is 90% of network capacity. It is noticeable that from Fig. 5.1 through Fig. 5.4, the total blocking performances of the four cases from best to worst should be RR with period = 0.01, FF with period = 0.01, RR with period = 0.1 and FF with period = 0.1 when network load is light, and should be FF with period = 0.01, RR with period = 0.01, RR with period = 0.1 and FF with period = 0.1 when a network is heavily loaded. From these results, it can be derived that for either FF algorithm or RR algorithm, the big increase in the blocking caused by *setup failures* results in a slight decrease in the blocking caused by *RWTA failures* when update period changes from 0.01 to 0.1.



a) logarithmic scale b) linear scale

Fig. 5.8. Compositions of blocking probabilities, RR algorithm, 16-node ring, update period = 0.01.

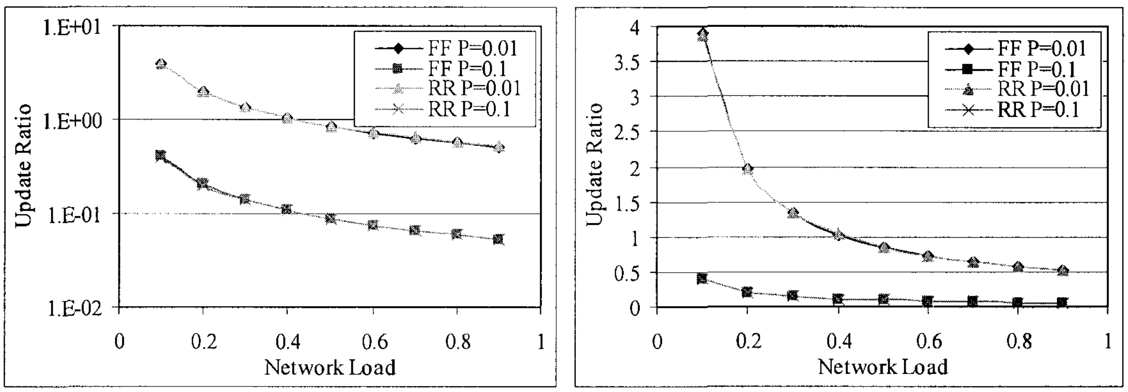
The contributions of the blocking caused by *setup failures* and the blocking caused by *RWTA failures* to the total network blocking are shown in Fig. 5.8 when link-state update period equals to 0.01 with RR algorithm in 16-node ring networks. The curve of the total blocking and the curve of the blocking caused by *RWTA failures* are very close to each other when network load is between 20% and 90% of network capacity, which indicates that the total network blocking is determined by the blocking caused by *RWTA failures* except for the case when network load 10% of network capacity.



a) logarithmic scale b) linear scale

Fig. 5.9. Compositions of blocking probabilities, RR algorithm, 16-node ring, update period = 0.1.

The situation changes when link-state update period increases to 0.1. The blocking caused by *setup failures* takes a dominant part in total network blocking when network load is between 10% and 20% while both the blocking caused by *setup failures* and the blocking caused by *RWTA failures* contribute a significant part to the total network blocking when network load is 30% and higher, shown in Fig. 5.9. RR algorithm is utilized as the dynamic RWTA algorithm in the simulation of 16-node ring networks.



a) logarithmic scale b) linear scale

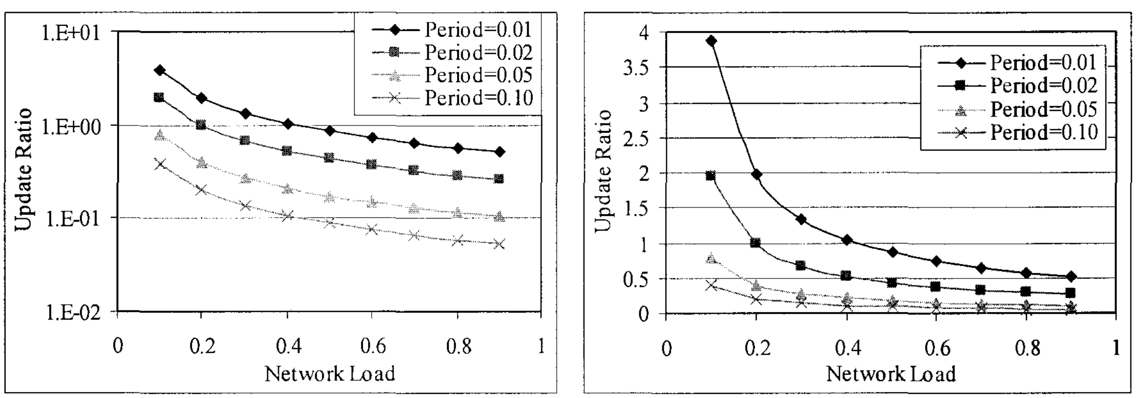
Fig. 5.10. Update ratio for periodic link-state update protocol with FF or RR algorithm, 16-node ring, update period = 0.01, 0.1.

Let the number of link-state exchanges that is required for instant link-state update scheme be defined as *regular update rate* and be normalized to 1. In addition, let the ratio of the number of periodic link-state exchanges to the *regular update rate* be defined as *update ratio* of the periodic link-state update protocol. Fig. 5.10 shows the *update ratios* for period = 0.01 and period = 0.1 in 16-node networks with both FF and RR algorithms. The 95% confidence intervals of all simulation results in the figure are lesser than the range of ±0.11% of the results. The *update ratio* of FF algorithm is very close to the *update ratio* of RR algorithm in both update period settings. However, blocking performances of the two algorithms have some slight differences, known from previous results. When network load increases from 10% to 90% of network capacity, *update ratios* decrease dramatically in both update period configurations because periodic link-state update protocol utilizes constant update period such that heavy network load results in coarse link-state update.

In case of link-state update period = 0.01, the numbers of periodic link-state exchanges that happened in 16-node ring networks for both FF and RR algorithms are about 4 times the number of instant information exchanges (*update ratio* ≈ 4) when a network is 10%

loaded. Still, the blocking performances of the two algorithms with periodic link-state update protocol are much worse than the blocking performance obtained with instant information exchange schemes. When network load reaches 90% of network capacity, with 0.51 *update ratio*, periodic link-state update protocol applying FF algorithm keeps a slight advantage in blocking performance compared with RR algorithm. This result implies that a lack of network resource is the dominant blocking reason in this case.

In case of link-state update period = 0.1, the blocking performance of the periodic link-state update protocol becomes notably worse than the performance in case of link-state update period = 0.01 and thus, even much worse than the performance of the instant information exchange scheme. The *update ratio* is approximately 0.4 when network load is 10% and the *update ratio* decreases to about 0.05 when network load is 90% for both FF and RR algorithms.



a) logarithmic scale b) linear scale

Fig. 5.11. Comparison of update ratio for periodic link-state update protocol, RR algorithms, 16-node ring, different update periods.

Since *update ratios* of both FF and RR algorithm are very close to each other, only the *update ratios* of RR algorithm are demonstrated here for different update period settings in 16-node rings (Fig. 5.11). The 95% confidence intervals of all simulation results in the figure are lesser than the range of ±0.11% of the results. The almost parallel curves in Fig. 5.11 a) indicate that the decreases of *update ratios* for different update period settings are proportionally similar with the increase of network load because the *update ratio* in periodic link-state update protocol is a function of network load.

5.1.3 Triggered link-state update protocol

Similar to the periodic link-state update protocol, the triggered link-state update protocol also includes two parts: *triggered link-state signaling*, and *connection operation*. In *triggered link-state signaling*, link-state update messages are exchanged once the accumulated state changes of wavelength and timeslot availability in links of a network reaches a pre-defined trigger threshold. The nature of triggered link-state update determines that the protocol overhead on processor and bandwidth resources for the exchange of link-state information rises with the increase of network load. The *connection operation* in the triggered link-state update protocol is similar to that in the periodic link-state update protocol. Dynamic RWTA for each QoS request is calculated on the source node of each connection based on the global link-state database on the node in order to find a route and then to select a feasible wavelength and timeslot solution for each connection. Wavelength and timeslot reservation command for each request is signaled to reserve wavelength/timeslots along the routing path of each connection.

To be comparable with the results in the periodic link-state update protocol, agile all-optical metro networks are modeled as single fiber ring networks. The dynamic RWTA problem is solved by the shortest path routing algorithm for routing subproblem and followed by the First-Fit wavelength assignment and First-Fit timeslot assignment scheme (FF) and the Random wavelength assignment and Random timeslot assignment scheme (RR) for the WTA subproblem.

Triggered link-state signaling: In triggered link-state signaling, link-state information is broadcasted when the build-up state changes reaches a certain trigger threshold. Hence, in the triggered link-state update protocol, *state* and *trigger* should be defined at the first place. The next step is to plan the procedure to notify each node in a network of the number of accumulated state changes since last link-state update, denoted as *nodal state change awareness*. Finally, *triggered signaling* is designed for the network-wide link-state information update.

State: A state in agile all-optical networks is defined as the state of the availability of a single timeslot on a wavelength of a fiber, busy or idle. Therefore, in a bidirectional ring network that has N nodes, F fibers in each direction of the ring, W wavelengths in each fiber and T timeslots in each frame, the number of states in the network is $2NFWT$. In this section, $F=1$ for single fiber ring networks.

Trigger: Of the two kinds of threshold triggers in the literature [Apos98], absolute threshold trigger and relative threshold trigger, the absolute threshold trigger is chosen here to initiate link-state information exchange in the triggered link-state update protocol designed for agile all-optical metro networks. The first reason to apply the absolute threshold trigger is the existence of the wavelength continuity constraint and the slotting constraint in the routing, wavelength and timeslot assignment problem for QoS bandwidth allocation, which needs exact wavelength and timeslot availability information. In addition, ring topology, which is designed as the topology of agile all-optical metro networks, offers one and only one route for any connections in networks according to the shortest path routing algorithm in dynamic RWTA algorithms despite the condition of wavelength and timeslot availability. Therefore, absolute threshold trigger can clearly represent the link-state changes (changes in the availability status of wavelength and timeslots) in networks and thus, is more appropriate to be the trigger in triggered link-state update protocol for agile all-optical metro networks than relative threshold trigger, which does not provide a comprehensible view regarding the state changes of wavelength and timeslot availability in network links.

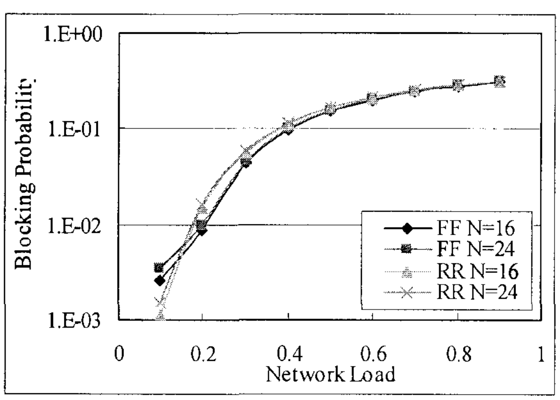
Nodal state change awareness: In a centralized-controlled network, the central controller has a complete view of the entire network. Hence, it is easy for the central controller to determine the moments to start network-wide link-state information updates. However, agile all-optical metro networks are designed to implement distributed control policy with the consideration of degree of coordination and network survivability. In distributed-controlled agile all-optical networks, each node is intelligently self-controlled to process connection operations with necessary information exchange with neighbors. Therefore, how to make every node in a network aware if the trigger threshold is reached is a good question. An *operating node notification scheme* is designed here to deal with this situation. In the *operating node notification scheme*, once a connection is set up or removed in a network, the source node of the connection is responsible for the notification of the number of state changes made by the setup or removal of the connection. Specifically, on the connection operation, the source node immediately generates a message regarding total number of state changes for the connection operation, and sends the message in the direction of the connection. As the signaling message goes around the ring, each node refreshes its register that records the number of accumulated state changes in the network ever since the last update of global link-state information. When the message arrives at the source node of the connection, the message is removed from the network. The register recording the number of accumulated state changes on each node in the network is reset to 0 at each time of network-wide link-state exchange.

Triggered signaling: In a network applying the triggered link-state update protocol, each node keeps accurate wavelength and timeslot availability information for its own outgoing links and potentially stale wavelength and timeslot availability information for the other links in the network. Nevertheless, the number of state changes made by each connection operation is updated instantly so that each node knows the accurate number of accumulated state changes in the network since the last update. The link-state changes in accordance to connection operations are saved in operating nodes only. When the accumulated state changes in the network hit the absolute trigger threshold, link-state updates are exchanged among the network nodes. Upon receiving the updates, each node refreshes its link-state database accordingly and resets its register that records the number of accumulated state changes in the network since the last link-state information exchange. For similar reasons observed in the study of the periodic link-state update protocol, the triggered link-state update protocol design here focuses on the research of impacts of stale information that arises from the triggered link-state update protocol, ignoring the effects of control message processing delays and propagation delays.

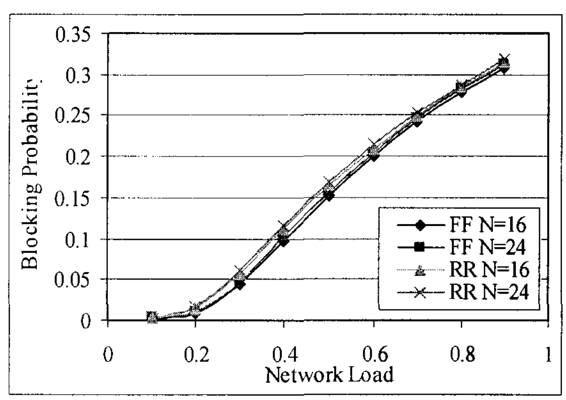
Connection operation: The connection operation in the triggered link-state update protocol is similar to that in the periodic link-state update protocol.

5.1.4 Simulations for triggered update protocol

By applying the triggered link-state update protocol, the blocking performances of dynamic RWTA algorithms of the Random wavelength and timeslot assignment (RR) and the First-Fit wavelength and timeslot assignment (FF) are compared for 16-node ring and 24-node ring networks under different absolute trigger thresholds. On average, a connection demand travels $N/4$ hops along the shortest path route and needs $T/2$ timeslots because the timeslot requirement per connection is uniformly distributed in $[1,T]$. Thus, the average number of timeslot state changes for a connection is $NT/8$. The trigger threshold is defined as 1 when $NT/8$ numbers of timeslots change their availability status. Agile all-optical metro networks here are modeled as single fiber ring networks with $W=8$ and $T=8$. The mean connection holding time is normalized to $1/\mu=1$ second. Different network traffic loads are modeled by varying the mean inter-arrival time between bandwidth requests. Blocked connection requests are discarded. For Fig. 5.10 through Fig. 5.19, the sizes of the 95% confidence intervals of the simulation results are decreased from ±1.8% of the results to ±0.4% of the results when traffic load increases from 10% of network capacity to 90% of network capacity.



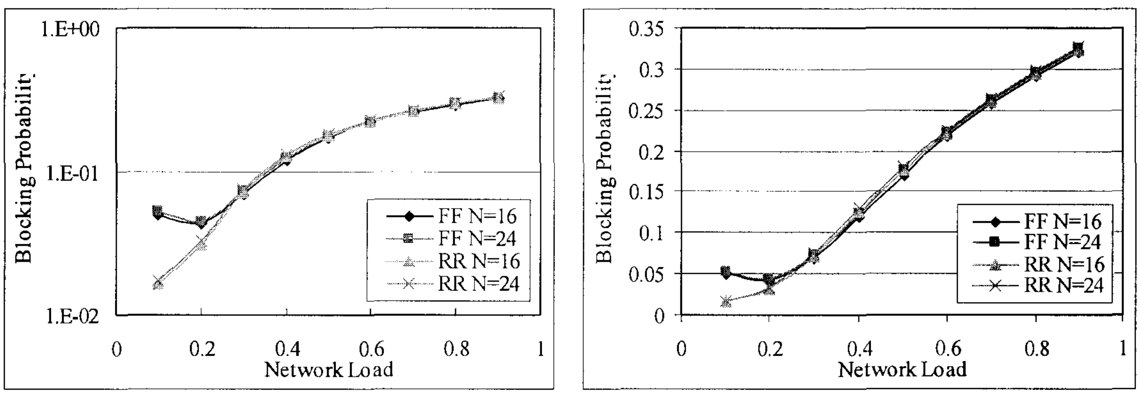
a) logarithmic scale



b) linear scale

Fig. 5.12. Blocking probabilities of FF and RR algorithms for 16-node ring and 24-node ring, the trigger threshold = 0.25.

The simulation result shown in Fig. 5.12 compares the blocking performances of FF and RR algorithms with triggered link-state update protocol for 16-node ring and 24-node ring networks when the trigger threshold equals 0.25, which imply that the network-wide link-state update is triggered when at least $NT/32$ timeslots change their states. In this case, RR performs better than FF only when the traffic load is lower than ~15% of the network capacity because in this case, the stale global information is more likely to cause FF to make incorrect routing, wavelength and timeslot assignment decisions than RR, which in turn may cause more blocking for FF than RR. When traffic load goes high, as more and more blockings are caused by a lack of available timeslots on wavelengths, FF shows better performance than RR and keeps this advantage to 90% of network load. Fig. 5.12 also shows that increasing nodes in a ring from 16 to 24 results in slight blocking performance degradation on the overall blocking probability.

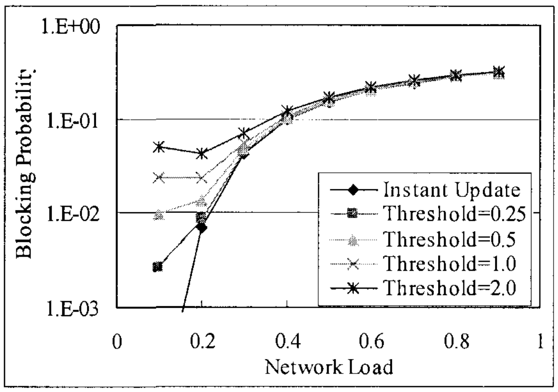


a) logarithmic scale b) linear scale

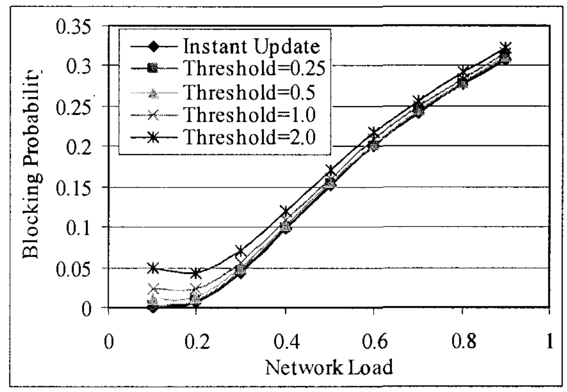
Fig. 5.13. Blocking probabilities of FF and RR algorithms for 16-node ring and 24-node ring, the trigger threshold = 2.0.

When the trigger threshold is set at 2.0 (trigger on state changes of at least $NT/4$ timeslots), it is shown in Fig. 5.13 that RR outperforms FF for up to 30% of network traffic load. This result indicates that FF, with triggered link-state update protocol, tends to make more mistakes in RWTA decisions based on more inaccurate global link-state information than RR algorithm, which is similar to the case in periodic link-state update protocol. However, different from the result in periodic link-state update protocol, as network load increases from 30% up, the performance of FF becomes better than RR. As it is known that FF is more sensitive to the staleness of link-state information than RR, this result means that the insufficient network resource caused blocking becomes a dominant part in total network blocking such that FF presents its advantage in the efficient network resource utilization when network load is 30% of network capacity and up. Still, the number of nodes in a network has only a minor effect on network blocking.

Fig. 5.14 compares the impacts of different trigger thresholds on network blocking probabilities of triggered link-state update protocol with FF algorithm for 16-node rings. As explained in previous sections, the total network blocking is composed of the blocking caused by *setup failures* and the blocking caused by *RWTA failures*. Network blocking for different trigger thresholds shown in Fig. 5.15 are decomposed to the blocking caused by *setup failures* shown in Fig. 5.16 and the blocking caused by *RWTA failures* shown in Fig. 5.14 for triggered link-state update protocol with FF algorithm in 16-node rings.



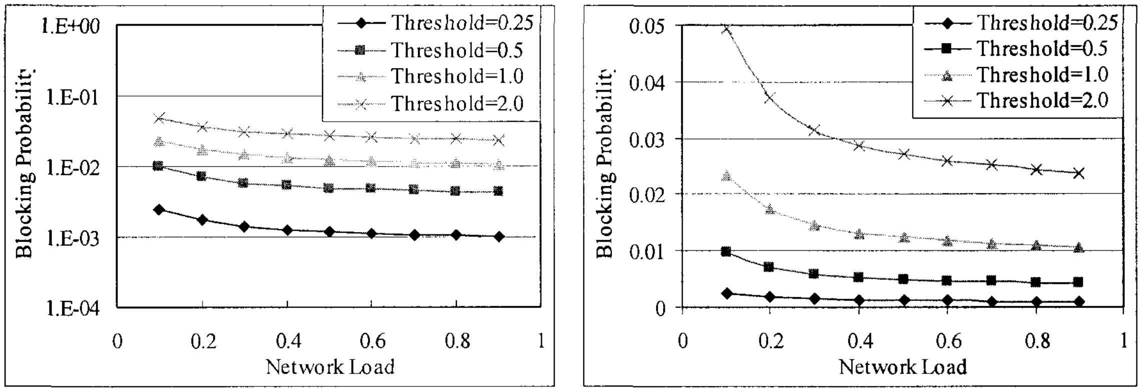
a) logarithmic scale



b) linear scale

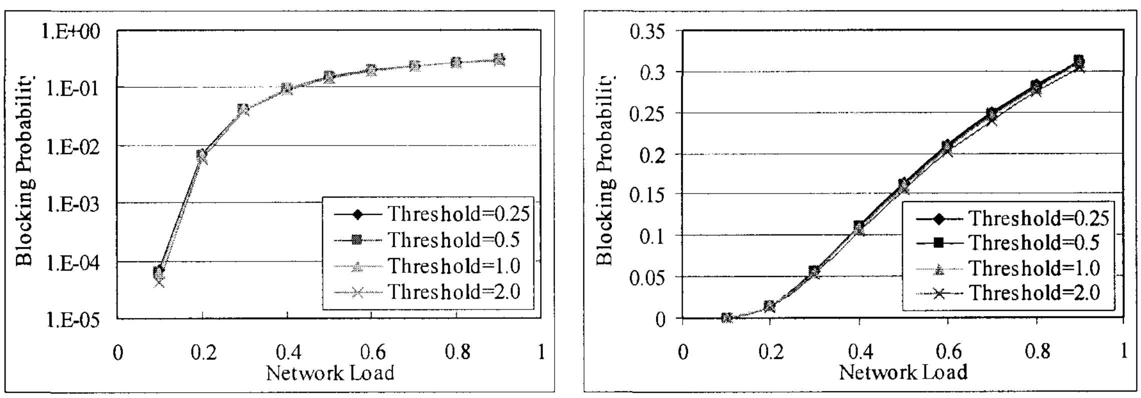
Fig. 5.14. Comparison of blocking probabilities, FF algorithm, 16-node ring, different trigger thresholds.

In Fig. 5.14, there are minor differences for the blocking performances of different trigger thresholds for triggered link-state update protocol when network load goes from medium to high. The blocking performance from best to worst is achieved by the trigger thresholds from smallest to largest, as expected. However, when a network is light loaded, significant blocking performance degradation is shown with the increase of the trigger threshold. The blocking curve for a threshold of 0.25 with the triggered link-state update protocol is almost overlapped with the curve of instant information exchange scheme except for the situation of very light network load (10%), while the curves of other trigger thresholds shows noticeable differences from each other, moving upwards from the curve of instant information exchange scheme. When the trigger threshold is 2.0, the blocking at 10% network load is bigger than the blocking at 20% network load, which is against the common idea that larger network load results in higher blocking. The reason for this phenomenon is explained in Fig. 5.15 and Fig. 5.16.



a) logarithmic scale b) linear scale

Fig. 5.15. Probabilities of the blocking caused by setup failures, FF algorithm, 16-node ring, different trigger thresholds.



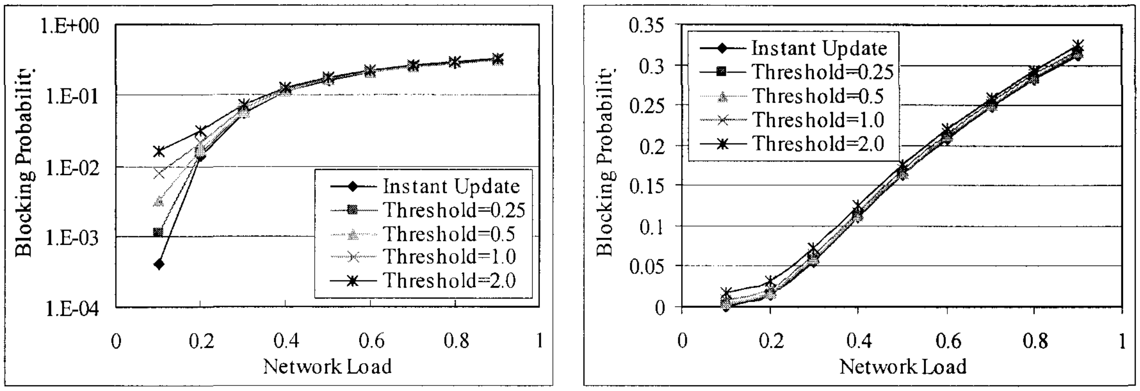
a) logarithmic scale b) linear scale

Fig. 5.16. Probabilities of the blocking caused by RWTA failures, FF algorithm, 16-node ring, different trigger thresholds.

The highest blocking caused by *setup failures* happens in the case of lowest network load for all settings of trigger thresholds shown in Fig. 5.15. The blocking caused by *setup failures* shrinks down drastically with the raise of network load from light to medium, especially when the trigger threshold = 2.0. The decline of the blocking caused by *setup failures* for a trigger threshold = 2.0 is from 0.049 to 0.037 when network load goes from 10% to 20% of network capacity, but the boost of the blocking caused by *RWTA failures* only changes from 0.00004 to 0.0055 with the adjustment of network load shown in Fig. 5.16. On the other hand, for any particular trigger threshold setting (e.g. threshold = 2.0), the significant increase of the blocking caused by *RWTA failures* (e.g. from 0.00004 to 0.0055) as the network load increases from 10% to 20% lessens the chances of the blocking caused by *setup failures* since the RWTA calculation is deployed in front of the reservation signaling in which the blocking caused by *setup failures* happens. This explains the high total blocking at 10% network load for a threshold = 2.0. When network load changes from medium to high, the blocking caused by *setup failures* decreases steadily because the problem of insufficient network resource rather than inaccurate link-state information becomes the primary difficulty in bandwidth allocation in this case. Thus, the blocking caused by *RWTA failures* turns into the dominant part in the total network blocking and rises drastically with the increase in network load. Nevertheless, the blocking caused by *setup failures* in the case of a threshold = 2.0 is radically higher than the other three cases of threshold settings.

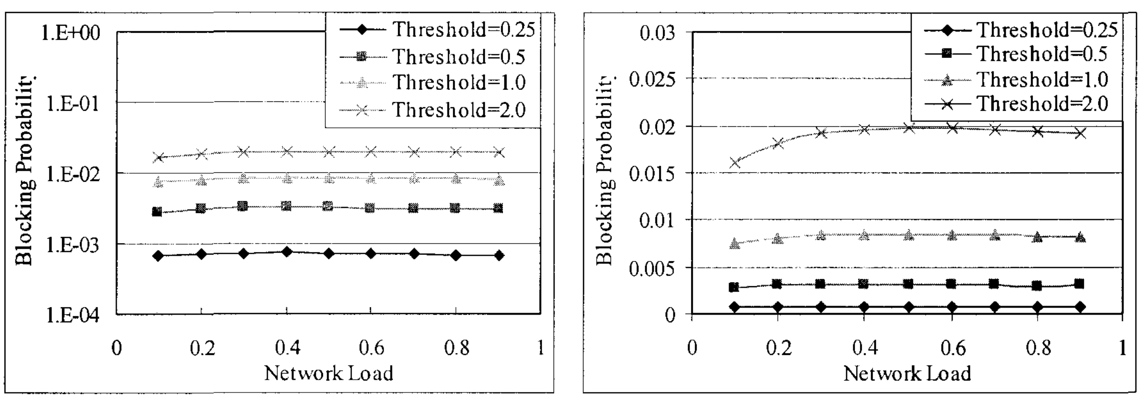
In Fig. 5.16, curves are almost overlapping with each other with subtle differences. The best performance is obtained by a threshold = 2.0, followed by a threshold = 1.0 and a threshold = 0.5. The worst performance corresponds to a threshold = 0.25. This sequence of performances from best to worst is just the reverse of the order of total blocking performances. Comparing Fig. 5.16 to Fig. 5.15, the performance differences in the blockings caused by *setup failures* are bigger than the differences in the blockings caused by *RWTA failures* such that the order in the total blocking performances shown in Fig. 5.14 for different trigger thresholds is the same as the order in the performances of the blocking caused by *setup failures*. On the other hand, the blocking caused by *setup failures* is a function of the staleness of link-state information. The big the trigger threshold, the large the blocking caused by *setup failures*. In addition, for different trigger threshold settings, the blocking caused by *RWTA failures* is correlated with the blocking caused by *setup failures*. An increase in the blocking caused by *setup failures* due to the growth in staleness of link-state information results in a reduction in the blocking caused by *RWTA failures*, but the reduced amount in the blocking caused by *RWTA failures* is smaller than the increased amount in the blocking caused by *setup failures*.

The impacts of different trigger thresholds on blocking probabilities in networks applying triggered link-state update protocol with RR algorithm for 16-node rings are compared in Fig. 5.17. The blocking caused by *setup failures* and the blocking caused by *RWTA* *failures* for different trigger thresholds, which add up to the total network blocking (shown in Fig. 5.17), are shown in Fig. 5.18 and Fig. 5.19 separately.



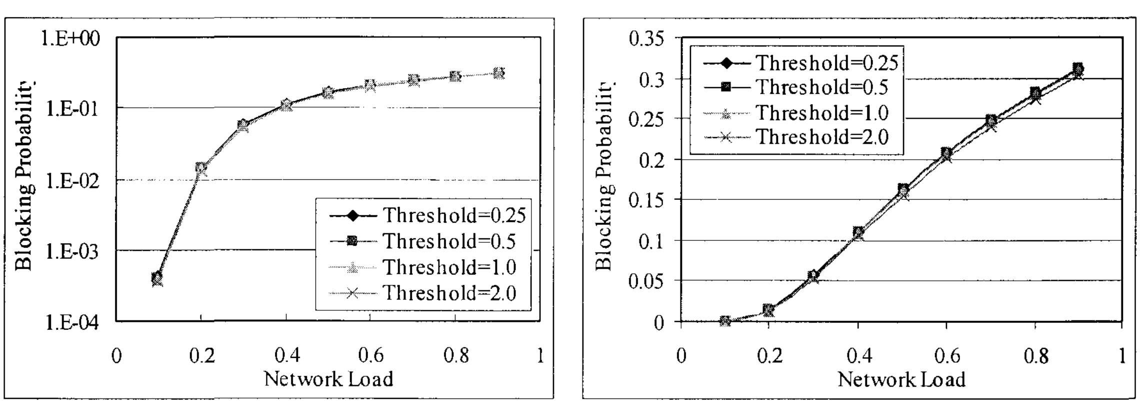
a) logarithmic scale b) linear scale

Fig. 5.17. Comparison of blocking probabilities, RR algorithm, 16-node ring, different trigger thresholds.



a) logarithmic scale b) linear scale

Fig. 5.18. Probabilities of the blocking caused by setup failures, RR algorithm, 16-node ring, different trigger thresholds.



a) logarithmic scale b) linear scale

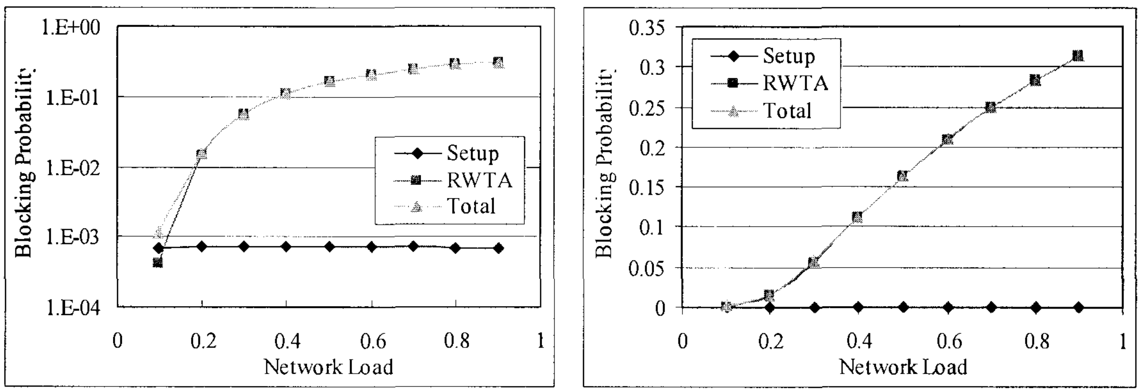
Fig. 5.19. Probabilities of the blocking caused by RWTA failures, RR algorithm, 16-node ring, different trigger thresholds.

In Fig. 5.17 b), the five curves for the instant information exchange scheme and four trigger threshold settings with triggered link-state update protocol with RR algorithm are almost parallel to each other. Similar to the cases with the FF algorithm, network blocking is a function of the trigger threshold and slightly increases when the trigger threshold becomes coarse. However, the performance gaps between the results with the triggered link-state update protocol and the result with instant information exchange scheme shrink subtly with the increase of network load. When network load corresponds to 10% of network capacity, the differences in the blocking with different trigger threshold settings is significant, which shows the sensitivity of the blocking performance to the staleness of link-state although the blocking performance with the RR algorithm is much better than the performance with the FF algorithm at 10% network load.

For different trigger thresholds, the blocking caused by *setup failures* enlarges with the augment of the trigger threshold shown in Fig. 5.18. For all cases of trigger threshold settings, the blocking caused by *setup failures* rises gradually when network load goes from low to medium, which shows that, for a certain trigger threshold, the trigger link-state update protocol with the RR algorithm is more sensitive to the increase of network load rather than the staleness of link-state information when network load is below medium. As the network load grows from medium to high, the blocking caused by *setup failures* lowers steadily in all cases of trigger threshold settings, which indicates that, for any particular trigger threshold setting, the difficulty of insufficient network resources instead of outdated link-state information dominates the trouble in connection accommodation in networks and the rapid increase in the blocking caused by *RWTA failures* (shown in Fig. 5.17) results in slight decrease in the blocking caused by *setup failures* with the growth of network load.

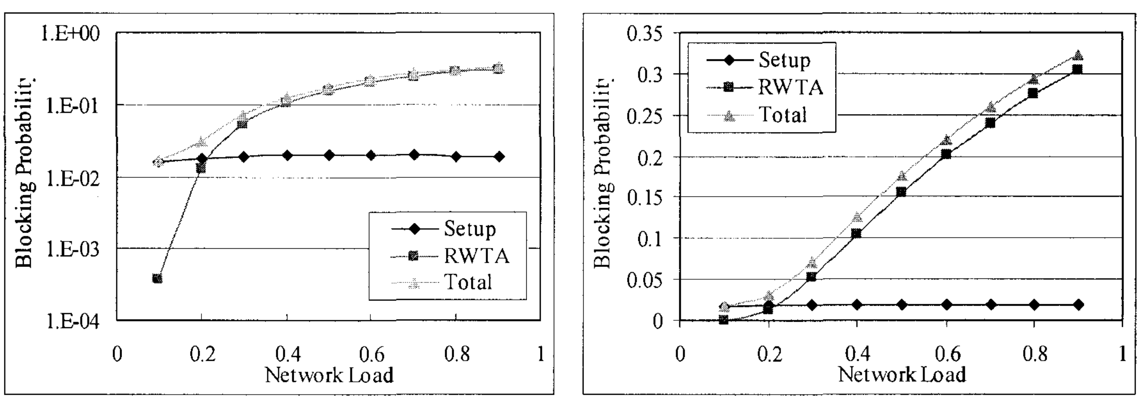
In Fig. 5.19, the blocking caused by *RWTA failures* shows similar performance curves with slight differences for various trigger threshold settings. Being the inverse order of total network blocking, the best performance of the blocking caused by *RWTA failures* is achieved by a trigger threshold = 2.0, followed by a trigger threshold = 1.0, 0.5 and 0.25.

The performance differences between different trigger thresholds become more obvious with the increase in network load.



a) logarithmic scale b) linear scale

Fig. 5.20. Compositions of blocking probabilities, RR algorithm for 16-node ring, trigger threshold = 0.25.



a) logarithmic scale b) linear scale

Fig. 5.21. Compositions of blocking probabilities, RR algorithm for 16-node ring, trigger threshold = 2.0.

The compositions of blocking probabilities of triggered link-state update protocol with RR algorithm in 16-node rings for a trigger threshold = 0.25 and a trigger threshold = 2.0 are shown in Fig. 5.20 and Fig. 5.21 separately. When the trigger threshold = 0.25, the curve of the total blocking and the curve of the blocking caused by *RWTA failures* approximately overlay with each other when network load is $\geq 20\%$ of the network capacity and have only a minor difference when a network is light loaded. However, when the trigger threshold becomes coarse and equals 2.0, the curve of total blocking is offset considerably up by the blocking caused by *setup failures*. As the total blocking of the triggered link-state update protocol with the two trigger threshold settings are similar, the increase in the staleness of link-state information increases the proportion of the blocking caused by *setup failures* in the total blocking and correspondingly reduces the proportion of the blocking caused by *RWTA failures* in the total blocking.

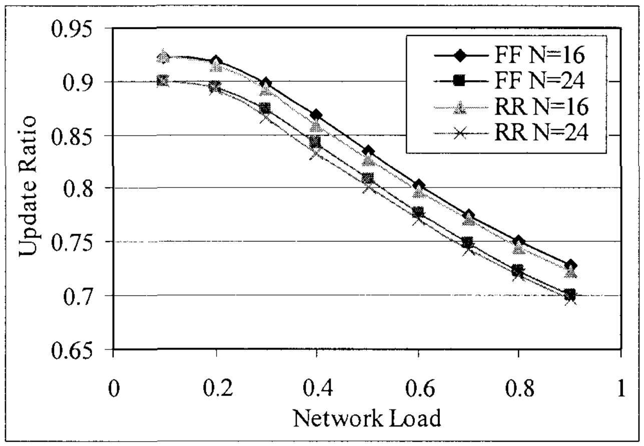


Fig. 5.22. Update ratio for triggered link-state update protocol with FF or RR algorithm, 16-node ring and 24-node ring, the trigger threshold = 0.25.

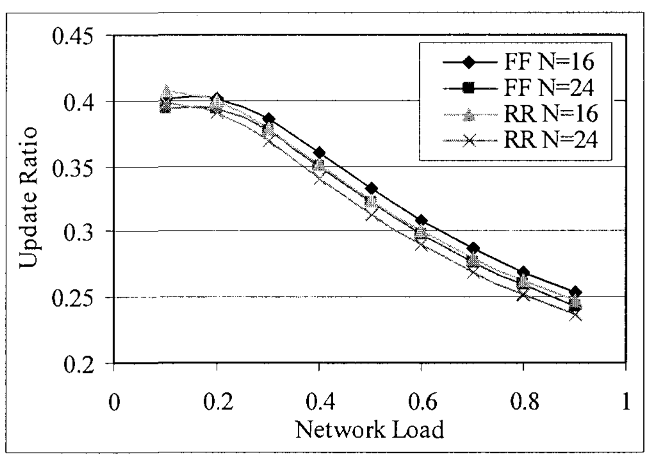
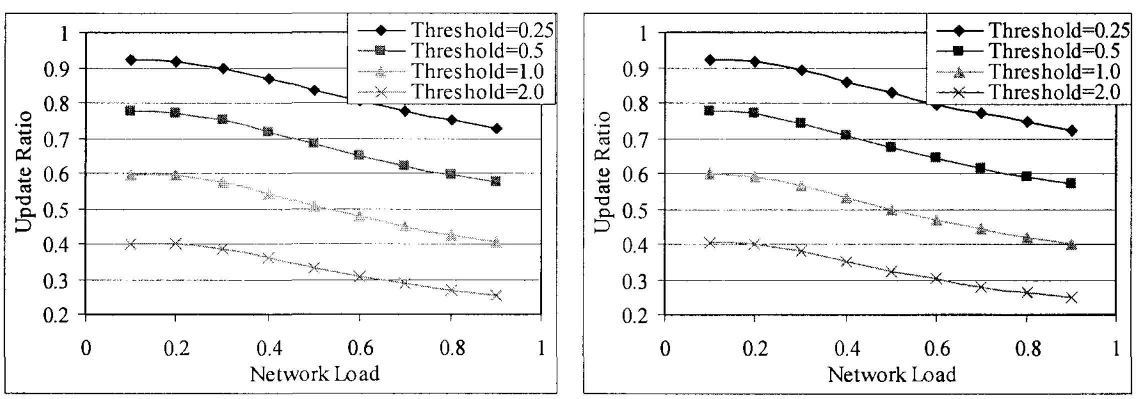


Fig. 5.23. Update ratio for triggered link-state update protocol with FF or RR algorithm, 16-node ring and 24-node ring, the trigger threshold= 2.0.

As the *regular update rate* is the number of link-state exchanges that is required for instant link-state update scheme and is normalized to 1, the *update ratio* is defined as the ratio of the number of triggered link-state exchanges to the *regular update rate* in the triggered link-state update protocol. Fig. 5.22 and Fig. 5.23 compare update ratios for triggered link-state protocol with FF or RR algorithm in 16-node rings by setting the trigger threshold = 0.25 and 2.0 separately. The 95% confidence intervals of all simulation results in the two figures are smaller than the range of ±0.18% of the results. When the trigger threshold = 0.25, the differences between the two algorithms and the two network node configurations are apparent. For the same network node configuration, the FF algorithm updates link-state information a little more frequently than the RR algorithm. For the same bandwidth allocation algorithm, the link-state information exchange in 16-node ring networks is more often than the exchange in 24-node ring networks. When the trigger threshold = 2.0, the update ratio gaps are small for different algorithms and network configurations. The differences in update ratio for different algorithms with a same network configuration become larger and the gaps for different network configurations with the same bandwidth allocation algorithm turn smaller. Nevertheless, with both trigger threshold settings, the triggered link-state update protocol with FF in 16-node rings has the highest update ratio and the protocol with RR in 24-node rings has the lowest update ratio. The small differences in update ratio result in small differences in network blocking probability. Shown in Fig. 5.12 and Fig. 5.13, triggered link-state update protocol with FF in 16-node rings achieves best blocking performance and the protocol with RR in 24-node rings corresponds to the worst performance when network load goes up from a certain point.



a) FF algorithm b) RR algorithm

Fig. 5.24. Comparison of update ratio for triggered link-state update protocol, FF or RR algorithm, 16-node ring, different trigger thresholds.

Fig. 5.24 compares the update ratios for different trigger thresholds in 16-node rings applying the triggered link-state update protocol with the FF algorithm (Fig. 24 a) and the

RR algorithm (Fig. 5.24 b). The 95% confidence intervals of all simulation results in the figure are smaller than the range of ±0.18% of the results. First of all, coarse trigger thresholds turn into low update ratios. Secondly, doubling the trigger threshold does not half the update ratio. Lastly, different from the dramatic drop in the update ratio with periodic link-state update protocol, for a certain trigger threshold, the update ratio in the triggered link-state update protocol decreases gradually. The steady reduction in update ratio with the increase in network load implies that networks are more favorable to the connections that need less network resources (less bandwidth requirement and/or fewer hops), which is easier to be accommodated into networks than the connections that need more network resources. Therefore, with the increase of network load, the trend, which is that networks tend to admit the connections that need less network resources and thus cause less state changes, results in the decrease in the frequency of network-wide link-state information exchange for a certain trigger threshold. Hence, the update ratio decreases gradually when the network load goes from low to high.

5.1.5 Comparison of periodic update protocol and triggered update protocol

This section includes two parts. In the first part, the periodic link-state update protocol and triggered link-state update protocol are compared for their update ratio and blocking performance. The simulation results shown in Fig. 5.25 and Fig. 5.26 are coming from graphs in previous sections for networks with $W=8$ and $T=8$. Thus, the 95% confidence intervals of all results in the following two figures have been explained in previous sections.

For the extreme case of the periodic update protocol where the update period = 0.01, the update ratio is much higher than the update ratio of the triggered update protocol with a trigger threshold = 0.5 when network load is between 10% and 75% of the network capacity and is slightly lower than the update ratio of triggered update protocol with a trigger threshold = 0.5 when network load is 75% and higher, shown in Fig. 5.25. This extreme case of update period = 0.01 is not applicable in networks since its update rate is much greater than the update frequency for instant link-state exchange scheme, which conflicts with the design objective of link-state update protocol to reduce the control traffic in link-state update process. However, the extreme case is utilized here for the comparison of the two protocols' performance.

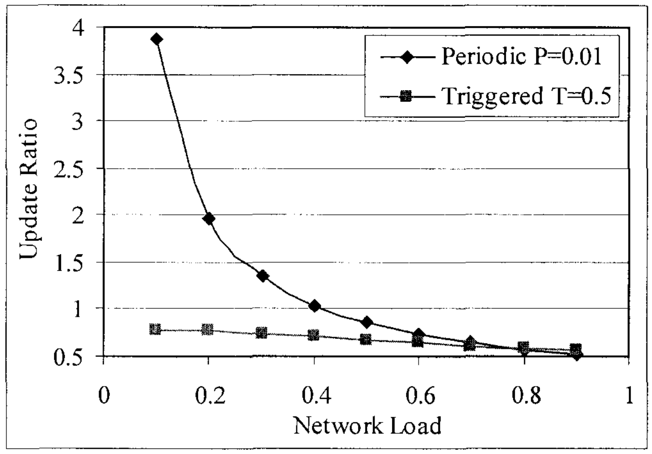
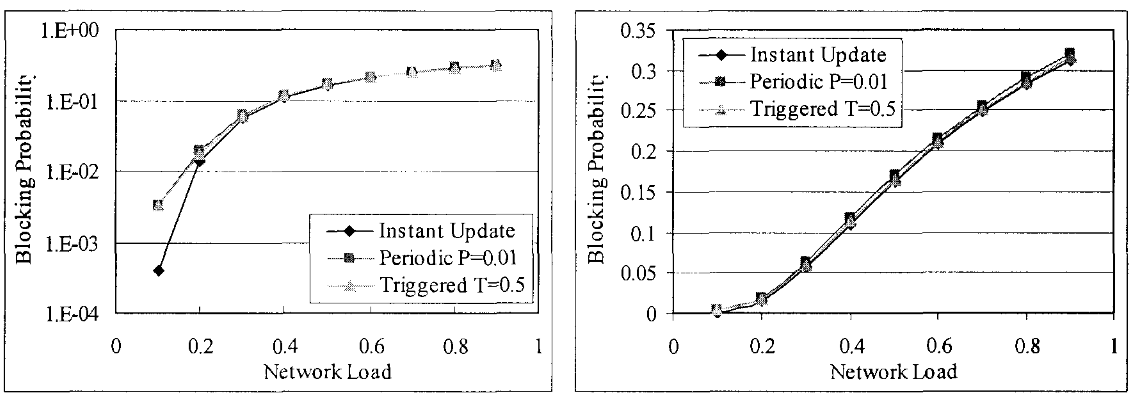


Fig. 5.25. Comparison of update ratio for periodic and triggered link-state update protocols, Period = 0.01, trigger threshold = 0.5 RR algorithms, 16-node ring.



a) logarithmic scale b) linear scale

Fig. 5.26. Comparison of blocking probabilities for periodic and triggered link-state update protocols, Period = 0.01, trigger threshold = 0.5 RR algorithms, 16-node ring.

Based on the update ratio shown in Fig. 5.25, the blocking performances of the periodic update protocol (update period = 0.01) and the triggered update protocol (the trigger threshold = 0.5) with RR algorithm in 16-node rings are compared in Fig. 5.26. When a network is 10% loaded, with update ratio of 3.87, the blocking probability of the periodic update protocol is slightly lower than the blocking probability of the triggered update protocol in which the update ratio is 0.78. When network load goes to 20% and higher, the update ratio of the periodic update protocol reduces dramatically from 1.96 to 0.52. In Fig. 5.25, the blocking performance of the periodic update protocol is worse than that of the triggered update protocol where the update ratio steadily decreases from 0.77 to 0.57. In the triggered update protocol, link-state exchange only happens when significant state changes take place in networks so that it has a definite objective and is imformative in information exchange. Therefore, the triggered update protocol offers more accurate link-state information with the same average update ratio than the periodic update protocol and thus, is chosen to be the link-state update protocol in agile all-optical metro ring networks when protocols with global link-state information are preferred.

In the second part of this section, based on the chosen triggered update protocol, FF and RR algorithms in the triggered link-state update protocol are compared for their overall blocking performance, the blocking caused by *setup failures*, and update ratio. First of all, from previous results total network blocking in Fig. 5.12 and Fig. 5.15, in ring networks deploying the triggered link-update update protocol, the FF algorithm outperforms the RR algorithm in overall network blocking when network load rises from *a particular point*. When network load is below the *particular point*, the FF algorithm underperforms the RR algorithm. The *particular point* in network load is a function of trigger threshold, moving upwards to higher network load while trigger threshold becoming coarse.

Secondly, Fig. 5.13 and Fig. 5.16 show the blocking caused by *setup failures* under various trigger threshold settings for FF and RR algorithms separately. By comparing the two figures, it is noticed that for a certain trigger threshold, the FF algorithm performs worse than the RR algorithm in the blocking caused by *setup failures* in all network load conditions although the FF algorithm is better than the RR algorithm in total blocking under some network load conditions. This result means that the portion of the blocking caused by *setup failures* in the total blocking with the FF algorithm is bigger than the portion of this kind of blocking in the total blocking with the RR algorithm.

Compared with the blocking caused by *RWTA failures*, the additional cost in the blocking caused by *setup failures* has three parts: control message signaling on nodes along routing paths of blocked connections, signaling bandwidth along routing paths, and temporarily reserved data bandwidth in unsuccessful bandwidth allocation. Considering that the FF algorithm has lower overall blocking probability than the RR algorithm under most traffic load conditions, the cost of data traffic bandwidth in the blocking caused by *setup failures* is cancelled by the superiority of the FF algorithm to the RR algorithm in bandwidth allocation under the network load conditions when the FF algorithm outperforms the RR algorithm in total network blocking. Therefore, in these network load conditions, the additional cost of the blocking caused by *setup failures* with the FF algorithm only includes signaling processing and signaling bandwidth.

Thirdly, for any particular trigger threshold, the update ratio in the FF algorithm is greater than that in the RR algorithm for a same network configuration shown in Fig. 5.20 and Fig. 5.21. For a certain trigger threshold, a high update ratio means more state changes happened in the networks. For the same number of connection operations (establishment and removal), more state changes in total means more state changes per connection. Therefore, the result implies that the FF algorithm is more favorable to connections that require more network resources than the RR algorithm. Thus, the FF algorithm is fairer in bandwidth allocation for connections with various QoS requirements in networks.

Based on the above analysis, the design of the bandwidth allocation algorithm for the triggered link-state update protocol depends on network service requirements in agile all-optical metro ring networks according to service-oriented design policy. Two solutions are proposed here according to different network service requirements. If switch processing ability is a critical issue in providing QoS service diversity to network users while maintaining a relatively acceptable blocking performance, it is proposed to use the RR algorithm in the triggered link-state update protocol for agile all-optical metro rings.

If network blocking is the critical issue in QoS requirements of network services, an adaptive triggered link-update protocol is proposed here. Satisfactory switch processing ability and sufficient signaling bandwidth are assumed in the protocol design. Firstly, the trigger threshold is configurable or automatic to adapt to network traffic requirement. Secondly, for a certain trigger threshold, the control database of each network node has the information of the *particular point* of network traffic load on which the FF algorithm and the RR algorithm switch their advantage in total blocking performance. Thirdly, the controller of each node adapts between the triggered update protocol with the RR algorithm and the triggered update protocol with the FF algorithm according to network load condition and trigger threshold settings, using the RR algorithm when network load is under the particular point and switching to the FF algorithm otherwise. In this way, minimum total network blocking is achieved.

5.2 Control protocol without global information

With global link-state awareness, a source node can make a dynamic RWTA decision as soon as a bandwidth request arrives, which eliminates the processing of intermediate nodes and destination node in the procedure of dynamic RWTA decision making and thus, achieves fast connection establishment. However, even with a significant amount of nodal signaling processing and signaling bandwidth consumption in global link-state information updating, connection setup may still be blocked because of outdated link-state information caused by propagation delay in the procedure of bandwidth allocation. In this section, this control overhead is eliminated by a proposed control mechanism using only local link-state information. In this case, the dynamic bandwidth allocation can only be implemented by combining dynamic RWTA algorithms with signaling and reservation schemes. Backward reservation instead of forward reservation is chosen to be the resource reservation scheme in this control protocol. Combined with the FF or RR algorithm, this control protocol still has the potential of having out-of-date link-state information because of the propagation delays in networks. For this reason, the impact of the stale information on the blocking probability of dynamic routing, wavelength and timeslot assignment algorithms is then investigated here.

5.2.1 Backward reservation protocol

In backward reservation protocol, no link-state update signaling is required since the protocol only utilizes local link-state information of each network node. In the two aspects of connection operation in agile all-optical networks using the backward reservation protocol, connection removal procedure is similar to the removal procedure detailed in Section 5.1.1. On the contrary, connection establishment is characterized by the close integration of signaling with link-state information collection, bandwidth allocation calculation and bandwidth reservation. Based on functions, the procedure of traffic accommodation for each connection in a network is divided into two parts: *signaling and bandwidth allocation calculation*, and *signaling and bandwidth reservation*. The objective of *signaling and bandwidth allocation calculation* is to find a feasible bandwidth allocation solution for each QoS connection request in a network. Nevertheless, the goal of *signaling and bandwidth reservation* is to preserve corresponding bandwidth for each connection according to the decision made by the bandwidth allocation calculation. As introduced in the literature review [Zang01], with only local link-state information, forward reservation needs to overbook all available resources on the path of a bandwidth request for a short time period, which may block successive requests requiring the same resources during the time period of overbooking. In order to avoid this situation, a backward reservation scheme is applied in the signaling and reservation for agile all-optical networks and the protocol is named thereby.

In the protocol design, agile all-optical metro networks are modeled as single fiber ring networks without loss of generality. The dynamic RWTA problem is solved by the shortest path routing algorithm for routing subproblem and followed by the First-Fit wavelength assignment and First-Fit timeslot assignment scheme (FF), or the Random wavelength assignment and Random timeslot assignment scheme (RR) for the WTA subproblem.

Signaling and bandwidth allocation calculation: In the control protocols with global link-state information available, bandwidth allocation calculation is done by the source node of each connection. However, with backward reservation protocol, each node in a network only has link-state information of its local outgoing links. Therefore, the source node of each connection request arriving at the network cannot solve the bandwidth allocation calculation independently. Instead, the bandwidth allocation decision is made by the cooperation of all network nodes along the routing path of each connection. In the procedure of *signaling and bandwidth allocation calculation* for each connection request, three steps are done in sequence: *routing and prescreening*, *request signaling*, and *bandwidth allocation calculation*.

Routing and prescreening: This step is done by the source node of each connection request. On the arrival of a new connection request, the source node calculates a routing path for the connection using shortest path routing algorithm, and then, checks if its outgoing link has enough resources for the connection setup. If the prescreening on the source node fails, the source node rejects the connection for the reason of insufficient network resources without trying to signal the connection through the network. This is one of the two places to find the blocking caused by *RWTA failures* in the protocol. Since the prescreening is based on local link-state information of the source node, there is no stale link-state information presented in this step and thus, the blocking is really caused by insufficient network resources. Otherwise, if the source node finds its local link is available for the connection setup, it starts signaling process.

Request signaling: Request signaling involves the interworking of all nodes along the routing path of the new connection request. Determined that local outgoing link can support the connection, the source node forms the initial *link-state information along the routing path* (path link-state information), which only holds the state information of the outgoing link on the source node. Then, the source node generates a signaling message and then sends the signaling message to the node on next hop of the routing path. The signaling message includes the routing decision, the initial path link-state information and the information from the new connection request, which contains the source node, the destination node and the number of timeslots required for the connection. Upon receiving the signaling message, each intermediate node of the connection identifies its local outgoing link on the routing path, adds the state of its local link to the incomplete path link-state information in the signaling message from the previous hop, and forwards the revised signaling message to the next hop. Finally, the signaling message arrives at the destination node of the connection request with complete path link-state information.

Bandwidth allocation calculation: When the destination node receives the signaling message requesting to set up the connection, it carries out WTA computations based on the complete path link-state information collected through the request signaling along the routing path. The bandwidth allocation calculation may fail to find a feasible solution to accommodate the new connection. This is another place where the blocking caused by *RWTA failures* happens in the protocol. In fact, some *RWTA failures* found at this point may be due to stale path link-state information on the destination node while other *RWTA failures* are strictly caused by insufficient network resources. The out-of-date path link-state information comes from the propagation delays accumulated in the procedure of path link-state information collection and transmission from the source node to the destination node of the new connection request.

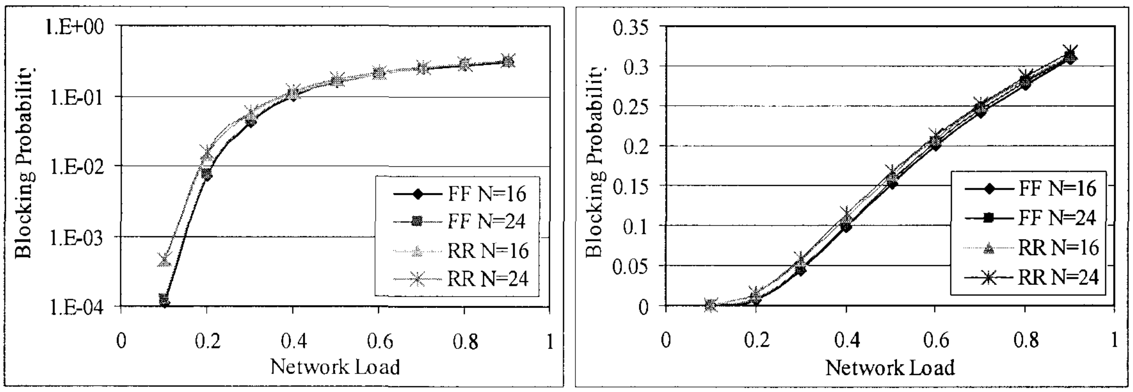
Signaling and bandwidth reservation: The signaling and bandwidth reservation start right after the *bandwidth allocation calculation* on the destination node. If the WTA calculation fails to find a feasible solution for the setup of the new connection, the destination node generates a *RWTA failure* notice and sends it upstream. No additional processing is needed on the intermediate nodes of the connection except forwarding the message upstream towards the source node. When the message arrives at the source node, the node rejects the connection request with the reason of insufficient network resources.

In the absence of *RWTA failures*, the destination node starts the procedure of reservation by initiating a message of reservation request that includes the WTA decision, and sending it back to the previous hop. The reservation procedure needs the involvement of all nodes on the routing path of the connection. Upon receiving the reservation request, each node carries out an admission test to check the availability of requested network resources for the setup of the new connection. If the requested wavelength and timeslots are available, the node reserves the corresponding resources and forwards the reservation request to the node on previous hop. Once the requested wavelength and timeslots are reserved in all links on the routing path of the connection, the network admits the new connection, committing the bandwidth reserved in each link of the routing path to the demand for the duration of the connection.

A *setup failure* occurs if the node deploying admission test finds that one or some requested timeslots on the requested wavelength are busy in its downstream link. The node where a *setup failure* is found generates two messages, a *setup failure* notice and a *reservation release* request, and sends them in two directions simultaneously. The *setup failure* notice is sent upstream towards the source node whilst the *reservation release* request is transmitted downstream towards the destination node of the connection. On receiving the *setup failure* notice, each intermediate node upstream along the routing path passes the notice over towards the source node without any additional processing. Once the source node receives the *setup failure* notice, it rejects the connection for the reason of *setup failure*. In the meantime, on receiving the *reservation release* request, each node downstream along the routing path releases the resources reserved on behalf of the new connection in its corresponding link before forwarding the request to the next hop towards the destination node. The process ends when the *reservation release* request reaches the destination node.

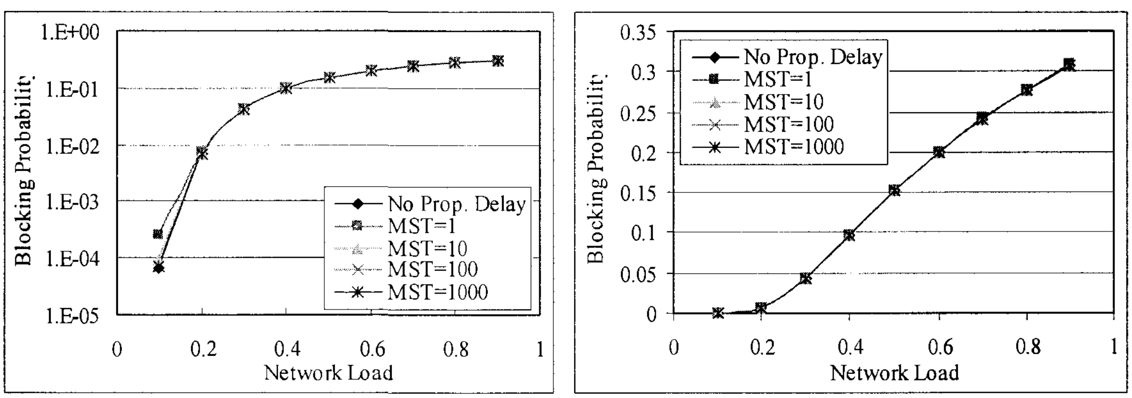
5.2.2 Simulations for backward reservation protocol

In this section, simulations are deployed to investigate the impact of the relationship between network propagation delay and the dynamic characteristic of network traffic on network blocking performance when the backward reservation protocol with the FF or the RR bandwidth allocation algorithm is applied in agile all-optical metro ring networks. Considering the span of metro networks, it is assumed that the distance between every pair of two adjacent nodes is 10 km. Then the propagation delay per hop is approximately 0.05 ms. With this basic assumption, as flexible bandwidth requests are always changing in time, the extent of the dynamic characteristic of network traffic is modeled by fixing a mean connection holding time $1/\mu$ for each network traffic condition. By this means, the relationship between network propagation delay and the dynamic characteristic of network traffic is formed in a relative way, where the blocking performance of a longer distance per hop with a certain mean service time can be represented by a corresponding shorter mean service time with a certain distance per hop. In the simulations, different situations of network traffic load are modeled by varying mean arrival rate λ. It is defined that $W=8$ and $T=8$, and it is assumed that blocked connection requests are discarded. For Fig. 5.27 through Fig. 5.33, the sizes of the 95% confidence intervals of the simulation results are decreased from ±3.3% of the results to ±0.4% of the results when traffic load increases from 10% of network capacity to 90% of network capacity.



a) logarithmic scale b) linear scale

Fig. 5.27. Blocking probabilities of the FF and RR algorithms for 16-node and 24-node rings, mean service time = 10 seconds.

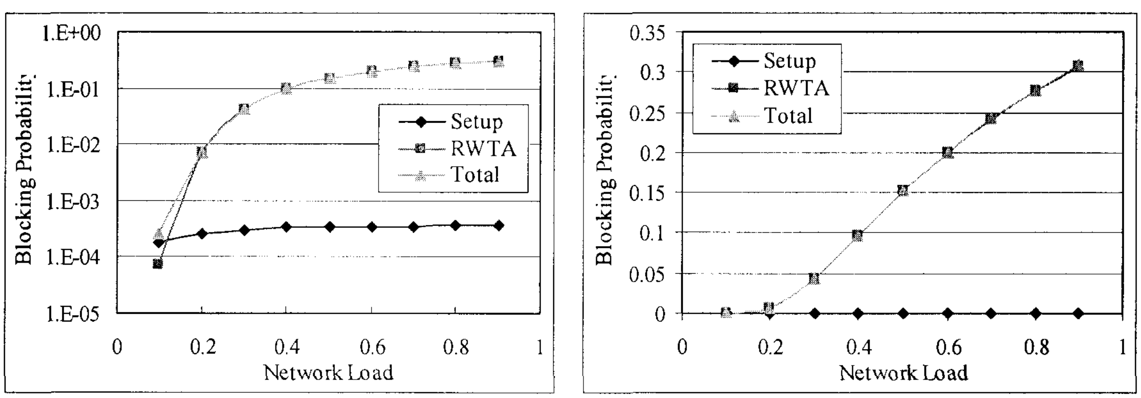


a) logarithmic scale b) linear scale

Fig. 5.28.Comparison of blocking probabilities, FF algorithm, 16-node ring, different MSTs.

Fig. 5.27 plots the blocking performances of the backward reservation protocol with FF or RR algorithm for 16-node and 24-node ring networks when the Mean Service Time (MST) $1/\mu$ of bandwidth requests is set to 10 seconds, which represents ring networks with 10 km per hop and providing service to traffic with MST equal to 10 seconds. The figure shows that FF has noticeable better performance than RR when network load is between 10% and 60% in both 16-node and 24-node rings. When network load goes from 60% up, the differences of blocking performance between FF and RR algorithms shrink because the shortage of network resources becomes the main reason of blocking. For either the FF or the RR algorithm, the blocking performance of 16-node rings is subtly better than the performance of 24-node rings. At 90% network load, the curve RR *N=16* overlaps with the curve FF *N=24*.

In Fig. 5.28, MST is varied from 1 to 10, 100 and 1000 seconds with fixed propagation delay of 0.05 ms per hop. The blocking performances of the backward reservation protocol for these cases are compared with the case of no propagation delay by applying the FF algorithm in 16-node ring networks. The figure shows that propagation delay has less impact on network blocking when the variation of traffic in networks becomes slower. There are no noticeable performance differences between the cases when network load is 20% and higher. When a network is 10% loaded, the case of MST=1.0 shows considerable performance degradation and the case of MST=10 demonstrates slight worse performance than the case of no propagation delay. When the MST becomes 100 or 1000, propagation delays almost have no impact on network blocking performance in networks applying backward reservation protocol.

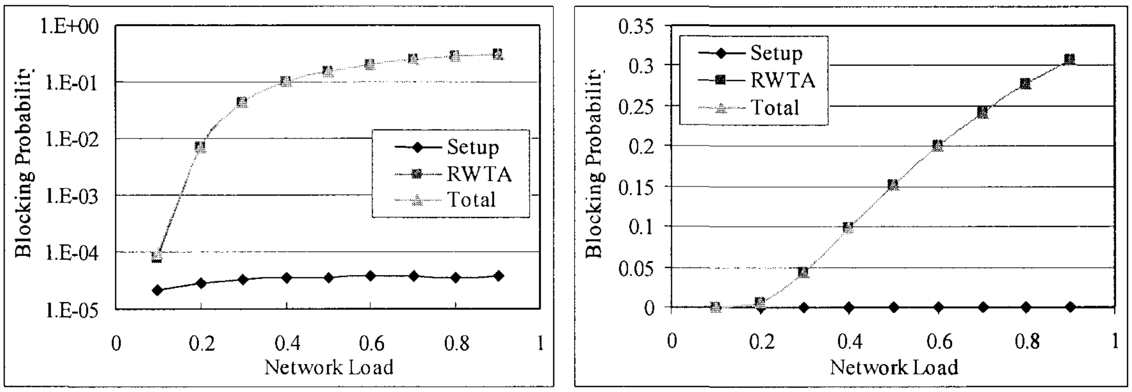


a) logarithmic scale b) linear scale

Fig. 5.29. Compositions of blocking probabilities, FF algorithm, 16-node ring, MST=1.

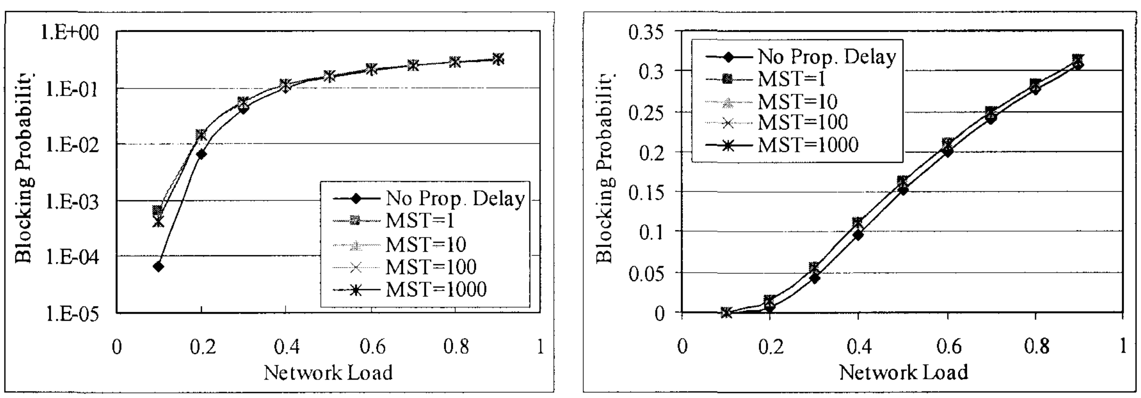
Fig. 5.29 and Fig. 5.30 demonstrates the portions of the blocking caused by *setup failures* and the blocking caused by *RWTA failures* in the total network blocking for 16 ring networks applying backward reservation protocol with FF algorithm when MST=1 and MST=10 separately. The blocking caused by *setup failures* in case of MST=1 is bigger than the same kind of blocking in the case of MST=10. In the case of MST=1, *setup failures* are the main reason of blocking when a network is 10% loaded. In the case of

MST=10, *RWTA failures* form the dominant part in the total blocking in any network load conditions.



a) logarithmic scale b) linear scale

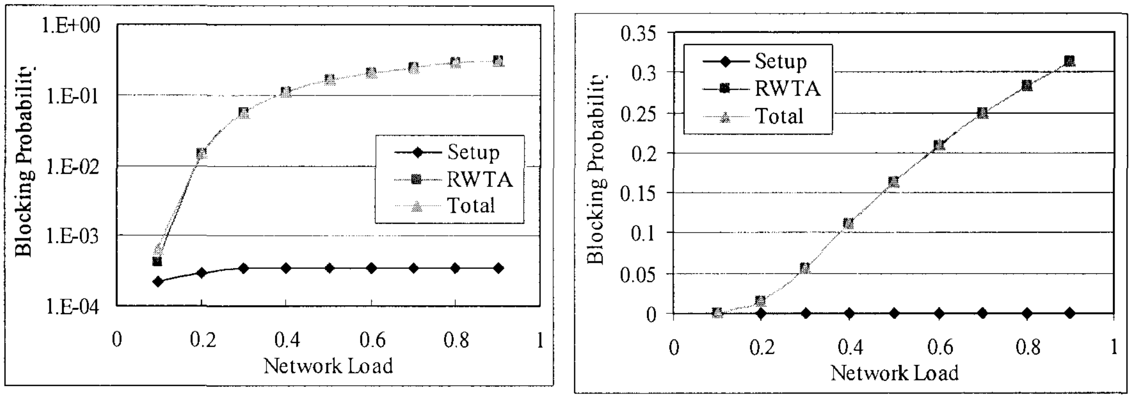
Fig. 5.30. Compositions of blocking probabilities, FF algorithm, 16-node ring, MST=10.



a) logarithmic scale b) linear scale

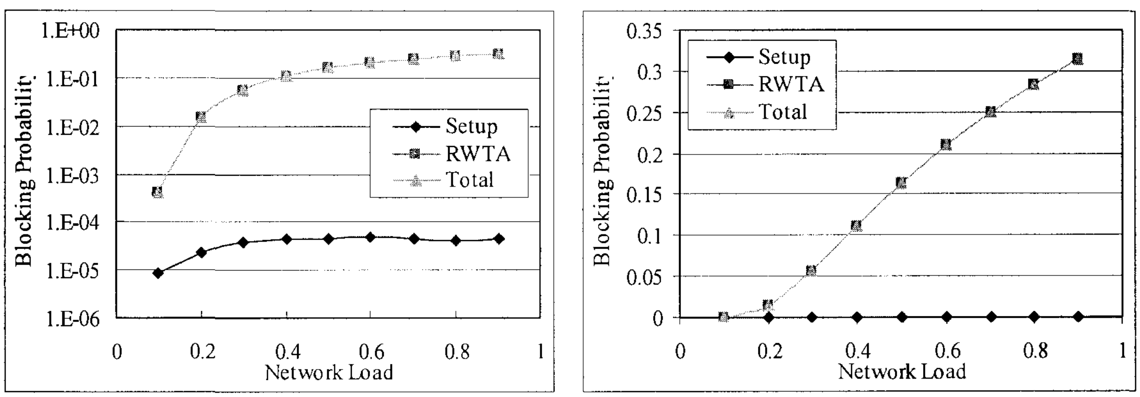
Fig. 5.31.Comparison of blocking probabilities, RR algorithm, 16-node ring, different mean service times.

Different from the results where the FF algorithm is used in backward reservation protocol, when the RR algorithm is employed with backward reservation protocol, considerable performance degradations in all cases of MST settings are seen compared with the case of no propagation delay in 16-node rings (Fig. 5.31), especially when network load is between 20% and 60%. Similar to the outcomes where the FF algorithm is used, with the RR algorithm, blocking performances are approximately the same for all cases of MST settings when network load is 20% and higher. When a network is very lightly loaded, the case of shortest MST shows the worst performance.



a) logarithmic scale b) linear scale

Fig. 5.32. Compositions of blocking probabilities, RR algorithm, 16-node ring, MST=1.



a) logarithmic scale b) linear scale

Fig. 5.33. Compositions of blocking probabilities, RR algorithm, 16-node ring, MST=10.

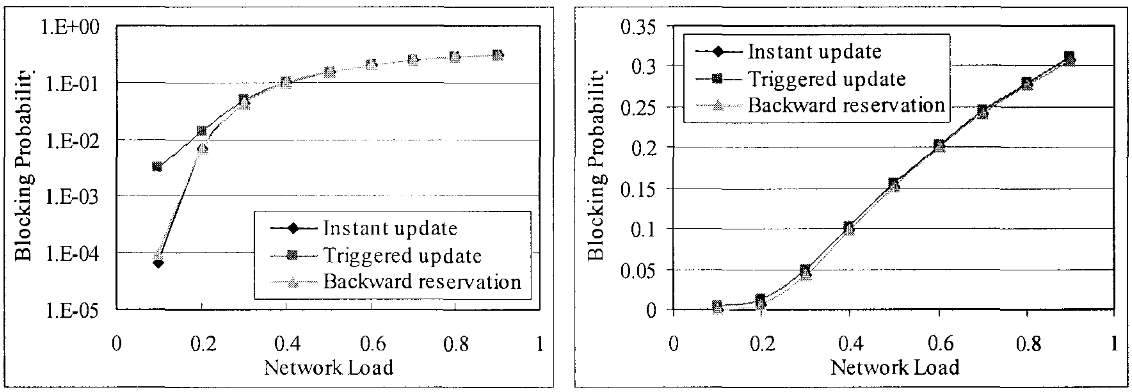
The portions of the blocking caused by *setup failures* and the blocking caused by *RWTA failures* in the total network blocking with the RR algorithm when MST=1 and MST=10 are separately shown in Fig. 5.32 and Fig. 5.33 for 16 ring networks. Comparing Fig. 5.32 to Fig. 5.29, the values of the blockings caused by *setup failures* are similar. The same is observed for the results shown in Fig. 5.33 and Fig. 5.30. However, when the RR algorithm is deployed, the blocking caused by *setup failures* is always a minority part in the total blocking at any network load condition for both cases of MST settings. Considering the noticeable performance difference between any case of MST setting and the case of no propagation delay, it is interesting to observe that the *RWTA failures* caused by stale path link-state information are the main reason of further performance degradation when propagation delays are considered in the blocking analysis.

Comparing the blocking performances of the FF and RR algorithms in the backward reservation protocol, the FF and the RR have similar amounts of the blockings caused by *setup failures* while the RR results in higher blocking caused by *RWTA failures* than FF. Even when the MST is set to 1 second, which represents network conditions where connections change extremely fast in time, propagation delays in metro networks are still very small compared with the rate of connection arrival and departure. As a result, the packed algorithm FF still significantly outperforms the random algorithm RR in the presence of network propagation delay. Therefore, backward reservation with FF algorithm is chosen for agile all-optical metro ring networks when only local link-state information is available in networks.

5.2.3 Comparison of triggered update and backward reservation protocols

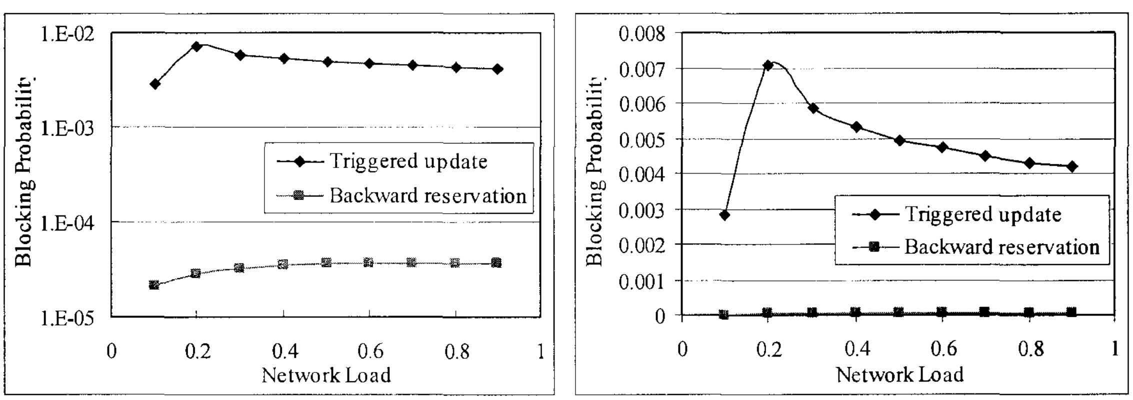
After the study of both kinds of control protocols with or without global link-state information availablity, the choice of the control protocol for agile all-optical metro ring networks should be concluded through careful comparison. The results in all figures of this section come from the results from previous sections of this chapter. First of all, the blocking performances of the triggered link-state update protocol and the backward reservation protocol are examined to demonstrate a perceptive comparison. In Fig. 5.34, blocking probabilities for the triggered link-state update protocol and the backward reservation protocol are compared with the instant update using the FF algorithm without considering of propagation delays for 16-node rings. In the figure, the triggered link-state update protocol utilizes adaptive the FF and RR algorithms to achieve best blocking performance with a trigger threshold = 0.5, which represents the update ratio of 0.5 – 0.7. The backward reservation protocol applies to the FF algorithm. Connection holding time is exponentially distributed with a MST = 10 seconds in both cases. The figure shows that the backward reservation protocol achieves better blocking probability than triggered link-state update protocol especially when a network is light loaded.

In fact, it is notable that the curve of triggered update protocol is derived with the ignorance of network propagation delay. Thus, the data may be worse if the consideration of propagation delays is combined into the performance analysis. For curves of total blockings (shown in Fig. 5.34), the portions of the blockings caused by *setup failures* are shown in Fig. 5.35.



a) logarithmic scale b) linear scale

Fig. 5.34. Comparison of blocking probabilities for the instant update with FF & no propagation delay, the triggered link-state update protocol with trigger threshold = 0.5 using adaptive RR+FF, and the backward reservation protocol with FF, mean service time = 10 seconds, 16-node ring.



a) logarithmic scale b) linear scale

Fig. 5.35. Comparison of the blocking caused by setup failures for the triggered link-state update protocol with trigger threshold = 0.5 using adaptive RR + FF, and the backward reservation protocol using FF, mean service time = 10 seconds, 16-node ring..

The blocking caused by *setup failures* for triggered link-state update protocol is a few hundreds times larger than the same kind of blocking for backward reservation protocol. On the other hand, of all the results from simulation runs shown in Section 5.2.2, no *RWTA failure* caused blocking is found during prescreening, i.e. all *RWTA failures* occur at the destination node. This result indicates that the cost of a *RWTA failure* occuring in networks applying the backward reservation protocol is higher than the cost of a *RWTA failure* happening in networks deploying the triggered link-state update protocol.

Secondly, in addition to the comparisons of simulation results, the connection setup procedures in the two kinds of control protocols with or without global link-state information is compared as follows for each new connection request. The kind of protocol with global link-state information is denoted as GA whereas the kind of protocol without global link-state information is denoted as NG.

- The node of RWTA calculation
  GA: on the source node
  NG: on the destination node
- Request signaling
  GA: not involve intermediate nodes
  NG: involves all nodes on the routing path, link-state information collection
- The possible positions where RWTA failures are found
  GA: on the source node (low cost)
  NG: on the source node (low cost) and the destination node (medium cost)
- Stale link-state information caused RWTA failures (high cost)
  GA: big amount, found on the source node
  NG: small amount, found on the destination node
- Reason of stale link-state information
  GA: delay in link-state update, much larger than propagation delay
  NG: propagation delay on routing path
- Direction of reservation
  GA: forward/downstream
  NG: backward/upstream
- *Setup failure* occurs
  GA: any node on routing path during forward reservation
  NG: any node on routing path during backward reservation

Therefore, NG needs more processing on intermediate nodes of a connection to collect link states on routing path, but maintains more accurate link-state information for connection setup.

5.3 Concluding remarks

In this chapter, two kinds of signaling and reservation control protocols are presented to accommodate dynamic traffic in agile all-optical metro ring networks. Both kinds of protocols have the potential to introduce outdated information for routing, wavelength and timeslot assignment. It is therefore studied for the impact of stale information on the blocking probability of dynamic RWTA schemes and found that the out-of-date link information degrades network blocking performance.

Of the two control protocols with global information, the triggered link-state update protocol with relative adequate link-state update rate has better blocking performance compared with the periodic link-state update protocol with extreme frequent link-state update rate. The reason behind this is that network-wide link-state exchanges in networks applying the triggered link-state update protocol happen when significant state changes occur; while network-wide link-state exchanges in networks applying the periodic link-state update protocol obey a periodic rule. Therefore, the triggered link-state update protocol is more state-change-oriented, achieves more accurate link-state information for the bandwidth allocation calculation, and thus results in less blocking caused by stale link-state information.

Evaluating the two kinds of control protocols presented in Section 5.1 and 5.2; the protocol with only local link-state information, the backward reservation protocol, which needs slightly more nodal processing and a slightly longer setup time but a much smaller amount of control traffic, achieves substantially better blocking performance than the protocols with global link-state information, the periodic link-state update protocol and the triggered link-state update protocol. This is due to the characteristic of ring networks, where static shortest path routing is preferable to other routing algorithms and hence adaptive routing (the usual advantage of the global link-state update scheme) does not add any value in the traffic accommodation in ring networks. This, in turn, makes the cost of global information updating less effective. In addition, the backward reservation protocol follows the design policy of information localization. Therefore, for metro ring networks, where the mean service time of network traffic is much greater than network propagation delays, the backward reservation scheme is the better control protocol for the dynamic traffic accommodation in agile all-optical metro ring networks.

In conclusion, this chapter has proposed two kinds of distributed signaling and reservation control protocols based on whether or not global link-state information is available, investigated the impacts of so-caused stale link-state information on network blocking performance, and compared call blocking probability of the two kinds of protocols for agile all-optical metro ring networks.

Ch. 6 Optical Layer Survivability

The present chapter introduces and describes some issues of network survivability for next-generation all-optical metro ring networks. Based on the service-oriented network planning policy, in this thesis, each design step starts from the point of view of end user requirements. As explained in Chapter 1, some network applications are critical, such as carrier-grade telephony, VoD, video conference, etc. These jitter-sensitive real time multimedia services require networks to maintain service continuity, which is realized through network protection and/or restoration. Although some layers operating above the optical layer may have their own protection and/or restoration mechanisms to provide either full or partial fault recovery to these critical services, it is believed here that optical layer protection and/or restoration is an important part in the network survivability system in order to provide adequate network availability.

Optical layer survivability is characterized for its speed, simplicity, and efficiency to detect and handle certain types of network faults such as fiber cuts and node failures. However, optical layer survivability cannot protect against all types of failures, such as failures at the client layers of the optical layer and failures between networks and end users. Thus, implementing survivability mechanisms at multiple layers is a must to protect networks from single failures and further, to survive network disasters. This allows the construction of autonomic networks that can provide high Quality of Service (QoS) to end users. In current existing networks, protection and restoration mechanisms in different network layers work independent of each other, resulting overlapping and omitting in network failure processing. The availability of next-generation networks aims to provide differentiated levels of protection for end users with different protection requirements. In the mean time, the network survivability system should be unified to guarantee all failures to be recovered and to avoid unnecessary function overlapping of multiple layers through the integration and cooperation of all layers.

With the above design policy, a multi-layer-integrated network survivability system is proposed here. The design considerations are as follows.

1. Fault identification: identify all types of failures that should be recovered by survivability systems.
2. Fault assignment: assign each type of failures to one network layer to process according to two rules.
   a. Rule 1: the layer can efficiently handle this type of failure;
   b. Rule 2: lower layer may provide faster recovery.
3. Local fault processing: each layer is responsible for the handling of the assigned types of failures including fault detection, localization and recovery.
4. Coordination strategy between layers to provide guaranteed network survivability: fault escalation from the fault recovery layer and cooperation from the client layers.
   a. Each fault recovery layer is responsible for escalating the failure to it client layer in survivability coordination.
   b. Each layer just above the fault recovery layer is responsible for monitoring the fault processing of the fault recovery layer, providing support to the fault recovery layer if necessary and taking corresponding actions if the fault recovery layer fails.

In the above considerations, items 1 and 2 are the steps that should be taken during the network design stage to ensure each type of faults to be properly processed at an appropriate layer or layers. Item 3 is the essential point for efficient fault recovery and should be realized through the design of a layered inter-nodal protocol that works during network operation. Item 4 provides an inter-layer-guaranteed mechanism through escalation, surveillance and cooperation between layers to realize the integrity of the survivability mechanism of all layers. This should be implemented by designing appropriate interoperation of inter-layer protocols that coordinates each layers in real time. In this way, the unified network survivability system can provide guaranteed protection and restoration for network services.

In the unified network survivability system, optical layer survivability needs only a small degree of coordination with client layers because the optical layer is transparent to layers operating above it. For the inter-layer coordination from the optical layer, fault escalation to client layers is considered here to be mandatory to offer guaranteed network survivability. The client layer awareness of the faults, which occur in live networks and are being processed in the optical layer, brings two benefits. With the fault awareness, the client layers may take necessary adjustments during optical layer fault recovery. In addition, when optical layer protection and restoration fails, the upper layer, which receives fault escalation from the optical layer, has an alternative way for fault detection, which may speed up fault recovery process in this layer. While the upper layers benefit from the fault escalation of the optical layer, the optical layer in turn needs some cooperation from the layers operating above it. The client layers should have corresponding tolerance for the faults from the optical layer, e.g. appropriate time out timer, such that a single failure at the optical layer does not result in an irrecoverable failure at the client layers. In this way, optical layer survivability forms a solid part in the multi-layer-integrated network survivability system.

6.1 Optical survivability for agile all-optical metro rings

The design of survivable agile all-optical metro ring network architectures here mirrors the SONET/SDH survivable architectures since SONET/SDH and agile all-optical networks are functionally similar. They are both connection-oriented multiplexed networks while SONET/SDH is based on synchronous digital multiplexing and WDM-TDM is based on wavelength and timeslot multiplexing. Similar to SONET/SDH, WDM-TDM survivable architectures can also be classified as either proactive protection or reactive protection. The distinction between the two mechanisms is largely based on the difference in the restoration time frame. Considering the service requirements for next-generation networks, the survivable agile all-optical network architectures are designed here to invoke a proactive protection scheme to assure guaranteed service recovery time for critical network services.

From the perspective of network infrastructure, optical layer survivability in agile all-optical metro ring networks needs to be well designed to properly divide interoperation and recovery functions at nodal redundancy, link capacity redundancy and traffic management. This thesis focuses on the traffic management design. The choice of protection schemes in traffic management is primarily determined by network service requirements or network switch capabilities. The service oriented design policy of agile all-optical networks determines that the network switches are deliberated to meet the requirements of network services whereas pervasive and ubiquitous network services call for differentiated QoS. Therefore, optical channel-based protection (path protection) is chosen here to be the optical layer protection scheme to provide differentiated protection services for traffic demands in agile all-optical metro networks. Furthermore, since the traffic in next-generation networks are highly dynamic with flexible bandwidth requirements and WDM-TDM multiplexing technique introduces wavelength continuity constraint and slotting constraint to traffic accommodation, shared channel protection policy is too complicated to be realized in agile all-optical networks. The dedicated protection scheme is selected for agile all-optical networks at the current stage thereby.

Compared with traditional optical networks, the survivability of agile all-optical metro ring networks is mainly characterized by two aspects: network service perspective (dynamic and flexible traffic demands) and network control perspective (distributed control mechanism with the goal of simplicity and efficiency). First of all, with optical channel-based protection for critical dynamic demands, WDM-TDM routed agile all-optical networks can provide differentiated QoS to user traffic on a single wavelength. In the optical layer, two classes of services in protection and restoration can be offered: protected service for critical user traffic and unprotected service. The unprotected service can be further classified to support either normal traffic or best-effort traffic.

Secondly, the ring topology of agile all-optical networks is the minimum-sized 2-connected topology that offers two separate routes between any pair of nodes that do not have any nodes or links in common except the source and destination nodes. In addition, ring topology is efficient from a fiber layout perspective since multiple sites can be interconnected with a single physical ring. Nevertheless, compared with networks adopting a mesh topology, a distributed-controlled network with a ring topology requires less degree of coordination between its network nodes because of the simplicity of the topology. This, in turn, makes it possible to implement simpler schemes for the control of protection and restoration. Furthermore, in SONET, Automatic Protection Switching

(APS) is usually used to handle link failures. However, Self-Healing Ring (SHR) has been proved as a more flexible scheme in SONET protection than APS since SHR protects networks from both link and node failures. By taking the advantages of the ring topology, SHR similar protection and restoration strategies can be deployed into survivable agile all-optical network.

Though the survivable agile all-optical network design brings about benefits to network services, it also introduces some technical difficulties. First of all, network-wide optimization of resource utilization can hardly be achieved in survivable agile all-optical networks. The distributed control mechanism makes network control systems robust and scalable. It also provides prompt services to network traffic demands without the delay of control overhead. However, with the distributed control mechanism, bandwidth utilization is controlled locally; thus, global optimization of bandwidth utilization can not be implemented either at connection setup stage or through rearrangement.

Another technical difficulty in survivable agile all-optical networks is the bandwidth reuse of backup lightpaths. With dedicated channel-based protection scheme, a backup lightpath is established at the same time when a primary lightpath is set up. If 1+1 channel-based protection is applied, traffic is transmitted simultaneously on the two disjoint routes from source node and destination node. Because of the characteristic of ring topology, the backup lightpath taking the route of ring side is usually much longer than the primary lightpath taking the route of span side. Therefore, a critical network connection consumes much more than twice the network resources that are required by normal connections requiring the same bandwidth and taking the same number of hops on shortest path. In this case, network bandwidth utilization efficiency is very low.

To improve bandwidth utilization efficiency, 1:1 channel-based protection can be deployed. With 1:1 channel-based protection, the backup lightpath of each critical traffic connection does not carry this critical user traffic when the primary connection is available. Thus, the bandwidth of all backup lightpaths in a network can be reused by some best-effort traffic in order to maintain network resource utilization to a certain level.

However, the bandwidth reuse of backup lightpaths is highly depending on the realization of wavelength and timeslot add/drop technique in agile all-optical switches because of characteristics of survivable agile all-optical networks. While providing flexible bandwidths for network traffic demands, backup lightpaths in a network may differ from each other with different source and destination nodes, and different bandwidth requirements. Moreover, WDM-TDM multiplexing technique confines wavelength and timeslot assignment with the wavelength continuity constraint and the slotting constraint. This thesis assumes that agile all-optical switches have the wavelength and timeslot add/drop flexibility in the bandwidth reuse of backup lightpaths.

The following are the design considerations here for optical survivability:

- Path protection.

  Each customer connection request, based on its traffic type, has the choice of whether or not the connection is protected.
- Minimized coordination between nodes.

  With 1:1 dedicated channel-based protection, a signaling protocol is needed to control fault detection and localization, and user traffic restoration with a reasonable range of coordination between nodes when a network failure occurs on the primary route.

6.2 Blocking in single-duct ring networks with protection

Most ring networks have two physical link ducts with one physical link duct in each direction, which is denoted as single-duct bidirectional ring networks. Thus, for each connection, there are only two link disjoint paths: the shortest path and the path opposite the shortest path on rings, which may take much longer route than the shortest path. In this section, network blocking is investigated for this kind of ring networks that provide protection and restoration.

6.2.1 Protection scheme for single-duct rings

The optical survivability proposed here is a service-differentiated channel-based protection for dynamic and flexible connection requests. Each connection request in networks is classified as critical traffic, normal traffic or best-effort traffic. Networks only provide protection and restoration for critical connections. When a critical connection request arrives at a ring network, a primary lightpath and a backup lightpath for the connection are set up simultaneously. The bandwidth allocation for the primary lightpath utilizes the shortest path routing combined with a FWTA algorithm. To protect the critical connection from fiber cuts and node failure, the backup lightpath takes the link-disjoint path from the primary route, i.e. the other part of the ring. Thus, the bandwidth allocation for the backup lightpath applies the same FWTA algorithm along the longer route of the two possible routes for the connection. If the bandwidth allocations for both primary and backup lightpaths are successful, the connection is set up. Otherwise, the connection is blocked.

For other QoS traffic, only one lightpath is trying to be set up for each connection request using shortest path routing and the same FWTA algorithm. The bandwidth of normal traffic is allocated from available network resources whereas the bandwidth of best-effort traffic is assigned from the bandwidth reserved for backup lightpaths. Each connection request is either served with a lightpath on a successful bandwidth allocation or blocked otherwise. When a failure occurs on the primary route of a critical connection, the best effort service(s) using the resources of the backup lightpath of the critical connection will be interrupted while the critical connection restoring its traffic to its backup lightpath. In this way, single-link bidirectional ring networks provide differentiated path protection for dynamic and flexible network traffic.

6.2.2 Rearrangement

The protection scheme in Section 6.2.1 offers differentiated protection and restoration service to network users in single-link bidirectional ring networks. However, because of the additional backup paths and the length of backup paths, the bandwidth allocation of critical services intuitively suffers from high connection blocking, which has also been proved through simulation. Suggested by the concept of rearrangement in [Mela83], a *rearrangeable bandwidth allocation scheme* for critical services is therefore proposed here aiming to accommodate new connection requests with the rearrangement of existing lightpaths.

The primary rule here is that rearrangement only occurs on backup lightpaths, leaving primary lightpaths to be untouched for real-time critical network traffic. The policies for the rearrangement in this work are listed below:

- When: rearrangement includes rearrangement calculation and rearrangement signaling while rearrangement calculation is performed in front of rearrangement signaling. Rearrangement calculation happens when the bandwidth allocation calculation fails to find a solution for either the primary or backup lightpath of a critical connection request. Rearrangement signaling only occurs when both primary and backup lightpaths of a new critical connection request can be set up with the rearrangement of some backup lightpaths and cannot be simultaneously established otherwise.
- Where: network-wide rearrangement will not happen for two reasons. Firstly, optical networks designed here apply distributed control mechanism such that a great deal of calculation and coordination are required if global rearrangement is implemented. Secondly, network traffic in agile all-optical networks is highly dynamic so that global rearrangement is too costly for connections with such short holding periods. Therefore, bandwidth allocation with local rearrangement is proposed here. The source node of each new critical traffic demand is responsible for the rearrangement calculation and signaling when the bandwidth allocation calculation deployed by the source node for either the primary lightpath or backup lightpath of the critical demand fails to find a solution.
- What: if rearrangement is necessary for the setup of a lightpath of a new critical traffic demand, all existing backup lightpaths starting from the source node in the same direction of the lightpath to be established are rearranged with the objective of accommodating the new lightpath through the wavelength and timeslot reassignment of the existing backup lightpaths.
- How: Rearrangement signaling is initiated by the source node of each critical connection request that can be set up through backup lightpath rearrangement. The signaling message controls other network nodes to make corresponding changes in network resource reservation for those backup lightpaths in order to establish the new critical connection.

In rearrangement calculation, the problem of making good use of available network resources to accommodate several lightpaths is an optimization problem. It is usually formed to be an integer linear programming problem, which needs intensive calculation. Notwithstanding, traffic in agile all-optical networks is fast-changing so that the reassignment needs simpler and faster calculation for rearrangement solutions. Therefore, in the rearrangement of backup lightpaths, heuristic approaches are considered here to solve the rearrangement problem in a timely manner.

The technical difficulty in the lightpath rearrangement is that the bandwidth requirement of each lightpath differs from another in two dimensions: the number of hops and the number of timeslots. Each lightpath may travel a different number of hops in a network whilst each lightpath in each hop may need a different number of timeslots. Three heuristic rearrangement approaches are proposed here. The first two approaches take the number of hops as the most important metric in measuring the difficulty in rearrangement, i.e. longest path first. The last approach considers the difficulties of the number of hops and the number of timeslots together.

In the *rearrangeable bandwidth allocation scheme*, the First-Fit algorithm is chosen to be the bandwidth allocation algorithm for new lightpath establishments since it is preferred in practice for its blocking performance, simplicity and fairness. The steps of the *rearrangeable bandwidth allocation scheme* for critical services are listed below:

- On the arrival of a new critical connection request, bandwidth allocation calculation is executed for the primary lightpath of the request.
- If the calculation fails to find any solution, then rearrangement calculation is carried out using a rearrangement algorithm in order to accommodate the primary lightpath of the new request. If this calculation still fails, the new request is blocked.
- When the bandwidth allocation for the primary lightpath of the new request succeeds either with or without rearrangement calculation, bandwidth allocation calculation is performed for the backup lightpath of the request.
- If the calculation fails to find any solution, then rearrangement calculation is carried out using a rearrangement algorithm in order to accommodate the backup lightpath of

the new request. If this calculation still fails, the new request is blocked; otherwise, continue to the next step, signaling and reservation.

- If bandwidth allocation solutions are found for both primary and backup lightpaths of the new connection request without the need of rearrangement, signaling is initiated by the source node to reserve bandwidth for the setup of the new connection. Else, signaling is started by the source node to rearrange network resource reservation for those backup lightpaths and to reserve bandwidth for the setup of the new connection.

Rearrangement calculation includes the rearrangement of certain backup lightpaths and the bandwidth allocation for the new lightpath. In fact, it calculates network link states supposing the non-existence of all existing backup lightpaths that start from the source node of the new demand in the same direction of the lightpath that is to be established. Then, with the calculated network link states, it strives to find Wavelength and Timeslot Assignment (WTA) solutions one-by-one for those lightpaths to be set up or to be rearranged according to a certain order. Those lightpaths travel a different number of hops and require a different number of timeslots. The difficulties in bandwidth allocation for those lightpaths are different because of the wavelength continuity constraint and the slotting constraint. The rearrangement calculation deals with the bandwidth allocation for both the new lightpath and those backup lightpaths together trying to serve the most resource demanding lightpath first.

The three heuristic rearrangement approaches to be presented differ from each other in the WTA algorithm used for rearrangement calculation and in the order of backup lightpaths to be rearranged. Two of the three approaches consider the number of hops as the metric of resource demand, and thus, execute WTA calculations for both the new lightpath and those backup lightpaths in the order of longest hop first. The first rearrangement heuristic utilizes First-Fit algorithm for bandwidth allocation in rearrangement calculation. The second rearrangement approach differs from the first heuristic in that it employs Most-Used algorithm for lightpath rearrangement.

The main difference between the third rearrangement approach and the above two heuristics is the sequence of lightpaths ordered to find WTA solutions one-by-one. The third approach considers the difficulties in the demand of hops and the requirement of timeslots together and takes two steps to do so:

- Build available timeslot lists in the order of longest hop first.

  Among all lightpaths to be established or to be rearranged, find the number of hop possibilities n_H, i.e. the size of the set H, where H is the set of possible numbers of hops. For each hop possibility $h \in H$ starting from the longest hop count to the shortest hop count, build an available timeslot list A_h such that a timeslot τ belongs to A_h if the number idle of hops for timeslot τ is greater than or equal to H hops. Note: τ differs from each other by both wavelength index and timeslot index.
- Employ bandwidth allocation for lightpaths to be established or to be rearranged in the order of "largest timeslot requirement first". Loop until all lightpaths are assigned, which indicates the success of rearrangement; or loop until a failure occurs in finding a WTA solution for a lightpath that is to be established or to be rearranged, which results in the blocking of the demand.
  a) Among all lightpaths that have not been processed, the lightpath that requires the largest number of timeslots is chosen to be processed next. Suppose this lightpath needs t timeslots and travels η hops.
  b) For the chosen lightpath, search a WTA solution in available timeslots lists A_γ, where $\eta \leq \gamma$, in the order of "shortest but enough hop count first" such that the wavelength assigned to the lightpath has minimum amount of capacity left after t timeslots on all η hops of links have been assigned to the lightpath.

The third approach tends to leave wavelengths that have more idle timeslots and timeslots that have longer idle hops to further lightpath rearrangements and further coming traffic demands.

The performances of the three heuristic rearrangement approaches are compared through simulation. All the simulation results in this section show the average network blocking probabilities for ring networks with $N=16$, $F=4$, $W=8$ and $T=8$. Without loss of generality, all connection requests arriving at networks are critical services that can only be set up if both primary and backup lightpaths can be established. In this way, by separating the effects of rearrangement from other factors, a clear view of blocking performances with or without rearrangement can be achieved. This assumption also simplifies the simulation process. In Table 6.1 and Fig. 6.1, the sizes of the 95% confidence intervals of the simulation results are decreased from ±4.5% of the results to ±0.26% of the results when traffic load increases from 10% of network capacity to 90% of network capacity.

Table 6.1 Blocking probability for networks with or without rearrangement

Network Load	0.3	0.4	0.5	0.6	0.7	0.8	0.9
NoR	2.822E-04	1.372E-02	6.808E-02	1.373E-01	1.993E-01	2.511E-01	2.939E-01
RFF	2.556E-04	1.282E-02	6.495E-02	1.330E-01	1.947E-01	2.470E-01	2.902E-01
RFM	2.505E-04	1.237E-02	6.340E-02	1.303E-01	1.914E-01	2.436E-01	2.867E-01
RTH	2.461E-04	1.224E-02	6.309E-02	1.297E-01	1.907E-01	2.423E-01	2.854E-01

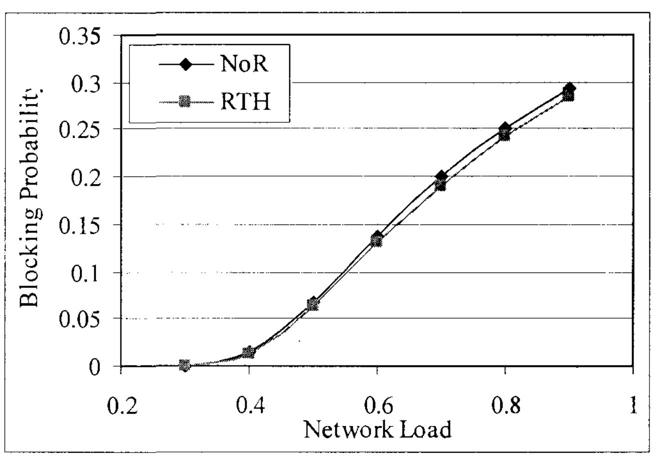


Fig. 6.1. Compositions of blocking probabilities for NoR and RTH.

Table 6.1 shows the simulation results of network blocking probabilities for four approaches with or without rearrangement in survivable networks, where $N = 16$, $F = 4$, $W = 8$, $T = 8$. The network load in the table indicates the total network load including both primary and backup lightpaths. NoR is the algorithm of First-Fit bandwidth allocation without rearrangement. RFF represents the algorithm of First-Fit bandwidth allocation and First-Fit rearrangement. RFM indicates the algorithm of First-Fit bandwidth allocation and Most-Used rearrangement. Both RFF and RFM utilize "longest hop first" as the order of lightpath rearrangement. RTH is the scheme employing First-Fit algorithm in bandwidth allocation for new connection requests that do not need rearrangement and the third rearrangement approach in rearrangement calculation.

It is demonstrated in Table 6.1 that rearrangement leads to a slight decrease in total blocking. Among the four algorithms, the best performance is obtained by RTH, followed by RFM and RFF. The case of no rearrangement, NoR, has the worst performance. The comparison of blocking performances for NoR and RTH is also demonstrated in Fig. 6.1. Compared with NoR, the performance improvement of RTH decreases from 12.8% to 2.7% when network load increases from 10% to 90%. This indicates that the rearrangement significantly improves network blocking performance when blocking is mainly caused by wavelength constraint and slotting constraint, and has marginal effects when blocking is primarily due to insufficient network resources. The average computational complexity of NoR is $O(FWTN\log(FWT))$ for the networks modeled in Chapter 3. The rearrangement approaches add some slight calculation, the calculation in finding the WTA solutions for n existing backup lightpaths starting from a network node, where n is the average number of existing backup lightpaths starting from a network node. According to simulation results, n is around 2. The average computational complexities for RFF and RFM are at the order of $O(FWTN\log(FWT))$. The average computational complexity of RTH is also at the order of $O(FWTN\log(FWT))$ since the WTA solution search is among some available timeslot lists and the size of the combination of all available timeslot lists is FWT. Therefore, whether or not to apply rearrangement depends on the comparison between the costs of blocking and the expenses in both rearrangement calculation and rearrangement signaling.

Table 6.2 compares the probabilities of blocking during the bandwidth allocation for either primary or backup lightpaths. In this table, the sizes of the 95% confidence intervals of the simulation results are decreased from ±4.9% of the results to ±0.29% of the results when traffic load increases from 10% of network capacity to 90% of network capacity. First of all, most blockings occur during the bandwidth allocation for backup lightpaths. Backup lightpaths always take much longer routes than primary lightpaths in ring networks. Secondly, when a network is lightly loaded, the accommodation of backup lightpaths, restricted by the wavelength continuity constraint and the slotting constraint, is much more difficult than the accommodation of primary lightpaths. When a network is heavily loaded, the accommodation of backup lightpaths tends to encounter more blocking because it requires more network resources while networks are in the condition of insufficient network resources. Thirdly, the probabilities of blocking during the bandwidth allocation for primary lightpaths take very close values for the four approaches. This indicates that rearrangement does not have really effects on this kind of blocking. Lastly, compared with NoR, the case of no rearrangement, three rearrangement approaches improve the performance of backup-lightpath accommodation caused blocking where RTH has the best performance, followed by RFM and RFF.

Table 6.2 Probabilities of blocking during the bandwidth allocation for either primary or backup lightpaths.

Network	Load	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Primary	NoR	3.750E-05	1.875E-03	9.901E-03	2.150E-02	3.388E-02	4.638E-02	5.875E-02
	RFF	3.389E-05	1.825E-03	9.731E-03	2.138E-02	3.374E-02	4.611E-02	5.827E-02
	RFM	3.417E-05	1.755E-03	9.453E-03	2.089E-02	3.308E-02	4.544E-02	5.750E-02
	RTH	3.398E-05	1.747E-03	9.519E-03	2.096E-02	3.335E-02	4.576E-02	5.811E-02
Backup	NoR	2.447E-04	1.184E-02	5.818E-02	1.158E-01	1.654E-01	2.047E-01	2.352E-01
	RFF	2.217E-04	1.099E-02	5.521E-02	1.116E-01	1.609E-01	2.009E-01	2.319E-01
	RFM	2.163E-04	1.062E-02	5.395E-02	1.095E-01	1.584E-01	1.981E-01	2.292E-01
	RTH	2.121E-04	1.049E-02	5.357E-02	1.087E-01	1.573E-01	1.965E-01	2.273E-01

The first half of Table 6.3 shows the probabilities of successful rearrangement while the second half of the table illustrates the probabilities of total blocking for the four approaches. In Table 6.3, the sizes of the 95% confidence intervals of the simulation results are decreased from ±4.5% of the results to ±0.26% of the results when traffic load increases from 10% of network capacity to 90% of network capacity. The comparison in the table points out that the increase in the successful bandwidth allocation for lightpaths after rearrangement do not directly result in the decrease of total blocking. This implies that blockings are mainly caused by the wavelength continuity constraint and the slotting or caused by network resource shortage, rather than inappropriate bandwidth allocation.

Table 6.3 Comparison of probabilities of successful rearrangement and probabilities of total blocking.

Network	Load	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Success.	RFF	3.332E-05	1.541E-03	7.308E-03	1.383E-02	1.873E-02	2.202E-02	2.420E-02
Rearrang.	RFM	4.500E-05	2.168E-03	1.062E-02	2.075E-02	2.880E-02	3.468E-02	3.879E-02
	TFM	4.802E-05	2.346E-03	1.169E-02	2.312E-02	3.257E-02	3.965E-02	4.508E-02
Total	RFF	2.556E-04	1.282E-02	6.495E-02	1.330E-01	1.947E-01	2.470E-01	2.902E-01
Blocking	RFM	2.505E-04	1.237E-02	6.340E-02	1.303E-01	1.914E-01	2.436E-01	2.867E-01
	RTH	2.461E-04	1.224E-02	6.309E-02	1.297E-01	1.907E-01	2.423E-01	2.854E-01

The above results show that the rearrangement approach RTH, which is designed according to the characteristics of potential traffic in agile all-optical networks, achieves best performance by attempting to make a good use of available network resources in the rearrangement calculation. Compared with the approach of no rearrangement in survivable networks, RTH makes blocking performance better at the costs of some additional processing, signaling and reconfiguration. However, the results also indicate that the main obstacle in improving blocking performance for survivable single-duct bidirectional ring networks is the length of backup routes. In single-duct rings, backup lightpaths always take very long routes and thus consume much more network resources than primary lightpaths, which constrains the bandwidth allocation in networks where the wavelength continuity constraint and the slotting constraint apply.

6.3 Blocking in dual-duct ring networks with protection

In survivable single-duct rings, it is inevitable that backup lightpaths always take much longer route than primary lightpaths. The intrinsic characteristic of the survivable single-duct rings causes two problems: inefficient network resource utilization and signal degradation on such long path in all-optical switching. Therefore, dual-duct ring networks are proposed for the protection in agile all-optical networks. In survivable bidirectional dual-duct rings, adjacent nodes are connected by four physical links with two duct-disjoint physical links in each direction. A link group is defined here to include the links in the same direction between two adjacent nodes in two physical ducts. With this kind of network configuration, the primary lightpath of each connection has two choices for the link route of the lightpath because of the dual-duct links in each direction and the presupposition of keeping one demand in one fiber. For a certain primary lightpath, there are three choices of duct-disjoint link routes to set up the corresponding backup lightpath. In this section, the protection scheme for this kind of ring networks is investigated and is compared with the protection scheme in survivable single-duct ring networks.

6.3.1 Protection scheme for dual-duct rings

The protection scheme here is similar to the protection scheme of single-duct rings. Based on optical path protection, the survivable dual-duct agile all-optical ring networks also aim to provide differentiated services for dynamic connection requests with flexible bandwidth requirements. Each connection request has the choice of being protected or not. For each critical connection request, two lightpaths should be set up simultaneously for the establishment of the connection. However, the protection scheme differs from the case of single-duct rings in that the dual-duct configuration provides more flexibility in the design of protection scheme.

The first step in the design of survivable dual-duct rings is to number the links in two ducts of each link group. Explained in Section 4.3, fibers in each link are numbered in order to pack traffic together by utilizing the wavelength continuity constraint and the slotting constraint to achieve better blocking performance. Similarly, here, the two ducts of each link group between two adjacent nodes in the same direction are numbered with either 1 or 2. Then, in one direction of ring networks, all links numbered 1 are denoted as duct-1 links while all links numbered 2 are named as duct-2 links.

With numbered link ducts, a proactive span switching and supplementary reactive ring switching scheme is proposed here for the survivable agile all-optical ring networks. Known from literature review, node failure rate is much lower than link failure rate because of the high redundancy design in nodal architecture [Kesh04] [Huan07]. In this thesis, the protection in survivable networks is therefore designed to protect critical services from link failures.

In proactive protection, the primary and backup lightpaths for a certain connection request are assigned to duct-disjoint paths. Both primary and backup lightpaths of a critical demand take the shortest path in order to efficiently use network resources and to lessen the points of failures on lightpaths. The bandwidths for the primary and backup lightpaths are reserved in two duct-disjoint links simultaneously at the time of connection setup for each critical network demand. For the setup of primary and backup lightpaths, neither duct-1 links nor duct-2 links are dedicated to accommodate either primary lightpaths or backup lightpaths. On the contrary, primary lightpaths are randomly assigned to either duct-1 links or duct-2 links. As a result, backup lightpaths, which is correlated with the setup of primary lightpaths, are also approximately evenly distributed between duct-1 links and duct-2 links. The objective of this design is to minimize the number of connections that need to be switched to backup lightpaths whenever a link failure occurs. When a transmitter or a receiver failure occurs or a link failure happens, proactive span switching begins. Those connections with primary lightpaths affected are routed on to their backup lightpaths.

As proactive span switching only protect critical services from link failures, supplementary reactive ring switching is therefore designed to react to node failures. Since traffic demands in agile all-optical networks are fast-changing, the bandwidth allocation solutions for the reactive backup lightpaths are not calculated in advance. Instead, the bandwidth allocation solutions are calculated for affected primary lightpaths when a node failure is identified. In reactive bandwidth allocation, backup lightpaths take the routes other than shortest paths for those connections, which are on the other side of rings and are usually much longer than shortest paths. After the bandwidth allocation calculation, affected critical connections are switched to those backup lightpaths until those backup lightpaths are set up through signaling and reservation. Thereby, reactive ring switching is slower than proactive span switching and is designed as a supplementary plan for critical service protection. The rest of this section focuses on the performance investigation of survivable dual-duct ring networks with the protection strategy of proactive span switching.

6.3.2 Redundancy comparison of single- and dual-duct rings

With proactive span switching, backup lightpaths in survivable dual-duct rings take shorter routes than backup lightpaths in survivable single-duct rings. Thus, the survivability strategy of proactive span switching in survivable dual-duct rings utilizes lesser capacity for critical network service protection than the survivability strategy in survivable single-duct rings. As a measure for the comparison of the overall capacity used by different survivability strategies, network redundancy indicates how efficient the survivability designs are in the use of network capacities for protection purpose.

Standard network redundancy R is defined as [Zhou07]

$$R = \{\sum_{i \in S}(\omega_i + s_i) - \sum_{i \in S}\omega_i^*\} / \sum_{i \in S}\omega_i^*$$

where S is the set of spans of a network, $\sum_{i \in S}\omega_i^*$ is the total network capacity required to accommodate all demands with shortest path routing, ω_i is the actual amount of network capacity needed for primary route of demands on span i, and s_i is the amount of network capacity needed for the protection of primary route of the demands on span i.

Considering a bidirectional ring network modeled in Chapter 3, the network has N nodes, F fibers in each direction, W wavelengths per fiber and T timeslots per frame. For a single-duct bidirectional ring, there are F fibers in each duct of one direction links. To keep the same network capacity, F fibers in each direction of the ring are equally divided between the two ducts of links in a dual-duct bidirectional ring. In the redundancy analysis of survivable single- and dual-duct rings, both primary and backup lightpaths for each connection have same bandwidth requirements. Hence, network capacity consumption in providing flexible bandwidth for network services is a common factor in both numerator and denominator of the redundancy equation and is canceled with each other in the equation. Therefore, the network redundancies of survivable single- and dual-duct rings are only affected by the hop counts of primary and backup lightpaths.

In both survivable single- and dual-duct rings with survivability strategies designed in this chapter, primary lightpaths are always routed on shortest paths. Thus, $\sum_{i\in S}\omega_i = \sum_{i\in S}\omega_i^*$.

According to the network model defined in Chapter 3, traffic in a ring network is evenly distributed among all nodes in the network. With the shortest path routing algorithm, the probability that the primary lightpath of a critical connection will travel H hops is

$$P_r(H=h) = 2/(N-1),\ h = 1,2,\ldots(N/2-1),$$

$$P_r(H=h) = 1/(N-1),\ h = N/2,$$

when N is even; or

$$P_r(H=h) = 2/(N-1),\ h = 1,2,\ldots(N-1)/2,$$

when N is odd. Then the total network capacity required to accommodate primary lightpaths of all demands with shortest path routing is

$$\sum_{i\in S}\omega_i^* = Q\left(\sum_{i=1}^{N/2-1} 2i + \frac{N}{2}\right) = Q\left[\frac{N}{4}(N-2) + \frac{N}{2}\right],$$

when N is even, or

$$\sum_{i\in S}\omega_i^* = Q\left(\sum_{i=1}^{(N-1)/2} 2i\right) = Q\left[\frac{1}{4}(N^2-1)\right],$$

when N is odd, where Q is a common factor. The total network capacity required for corresponding backup lightpaths in survivable single-duct rings is

$$\sum_{i\in S}s_i = Q\left[\sum_{i=1}^{N/2-1} 2(N-i) + \frac{N}{2}\right] = Q\left[\frac{3}{4}N(N-2) + \frac{N}{2}\right],$$

when N is even, or

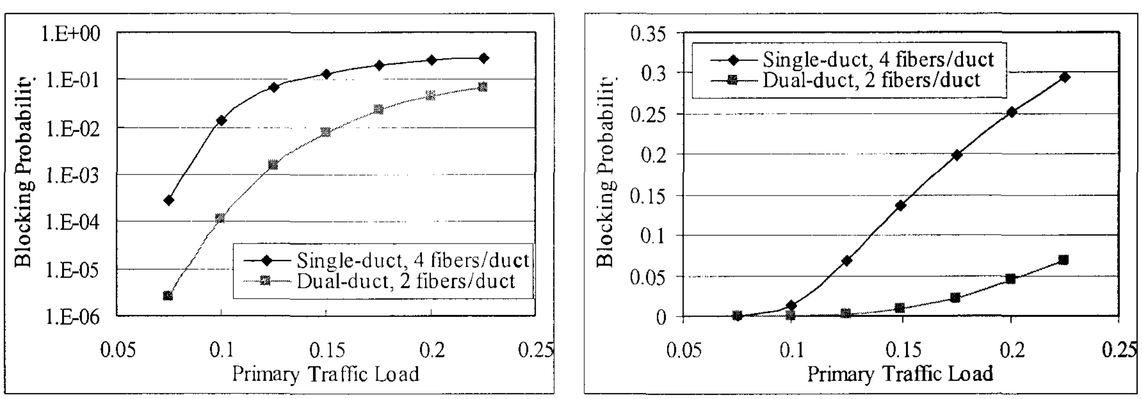
$$\sum_{i\in S}s_i = Q\left[\sum_{i=1}^{(N-1)/2} 2(N-i)\right] = Q\left[\frac{3}{4}(N^2-1)\right],$$

when N is odd. Therefore, network redundancy of survivable single-duct rings is

$$R = \sum_{i\in S}s_i / \sum_{i\in S}\omega_i^* \approx 3.$$

In survivable dual-duct rings with proactive span switching protection strategy, both primary and backup lightpaths take shortest paths. Thus, $\sum_{i\in S}s_i = \sum_{i\in S}\omega_i^*$. As a result, the redundancy of survivable dual-duct rings is $R = 1$. Therefore, theoretically, the network capacity to set up both primary and backup lightpaths for a critical demand in survivable dual-duct rings is the half of the network capacity required by both primary and backup lightpaths for the same critical demand in survivable single-duct rings.

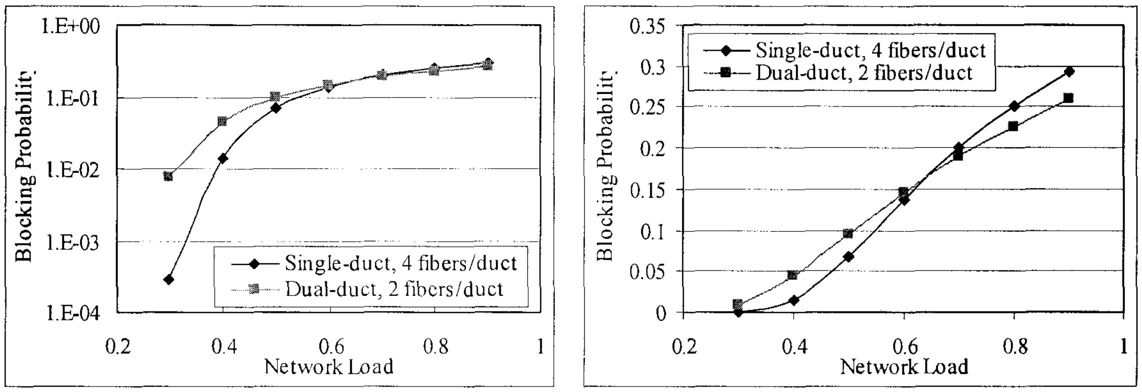
The performances of the survivability strategies in single- and dual-duct ring networks are compared through simulation. To separate the effects of survivability strategies from other factors, the simulations only focus on traffic accommodation for critical services that can only be set up when both primary and backup lightpaths are able to be established. All the simulation results in this section show the average network blocking probabilities for ring networks with *N=16*, *W=8* and *T=8*. In Fig. 6.2, Fig. 6.3 and Fig. 6.5, the sizes of the 95% confidence intervals of the simulation results are decreased from ±4.2% of the results to ±0.27% of the results when traffic load increases from 10% to 90% of network capacity. The 95% confidence intervals of all simulation results in the Fig. 6.4 and Fig. 6.6 are lesser than the range of ±0.06% of the results.



a) logarithmic scale b) linear scale

Fig. 6.2. Blocking probabilities in single- and dual-duct networks with equal network capacity and equal amount of primary traffic load.

Simulation results shown in Fig 6.2 demonstrate the blocking probabilities in single-and dual-duct ring networks with equal network capacities and an equal amount of primary traffic load. The single-duct rings have 4 fibers in each direction while the dual-duct rings also have 4 fibers in each direction with 2 fibers in each duct. Primary traffic load indicates the traffic load brought by the establishment of primary lightpaths. In this case, dual-duct rings have much better blocking performance than single-duct rings. The reason behind this is that the backup lightpaths in dual-duct rings take shorter routes than the backup lightpaths in single-duct rings, and therefore, utilize lesser network resources.



a) logarithmic scale b) linear scale

Fig. 6.3. Blocking probabilities in single- and dual-duct networks with equal network capacity and equal amount of network traffic load.

Fig 6.3 shows the blocking probabilities in single-and dual-duct ring networks with equal network capacities and equal amount of total network traffic load. The single-duct rings have 4 fibers in each direction while the dual-duct rings also have 4 fibers in each direction with 2 fibers in each duct. In this case, the amount of primary traffic load in dual-duct rings is twice the amount of primary traffic load in single-duct rings. When network load is light, dual-duct rings underperforms single-duct rings. The reason behind this is that dual-duct rings have less flexibility in bandwidth allocation with only 2 fibers in each duct. When network load goes from 68% to higher, the performance of dual-duct rings becomes better than that of single-duct rings. This is due to the fact that backup lightpaths are routed to longer routes in single-duct rings than in dual-duct rings, and lightpaths with short hop counts are more favorable in bandwidth allocation than lightpaths with long hop counts when a network is heavily loaded.

The two curves illustrate network capacity utilizations in single- and dual-duct rings with equal network capacity and equal amount of total network traffic load (Fig. 6.4). The network capacity utilizations shown in Fig. 6.4 are achieved when single- and dual-duct ring networks demonstrate the blocking performances shown in Fig. 6.3. By comparing the two figures, high blocking results in low capacity utilization when network load is between 35% and 65%. In single-duct rings, whenever a critical connection is established, the primary lightpath and backup lightpath of the connection always add up to the path of the entire ring, i.e., critical connections in single-duct rings have a fixed total path length. However, dual-duct rings with only 2 fibers in each duct have limited flexibility in bandwidth allocation, and therefore, becomes more favorable for critical connections with short lightpaths based on proactive span switching strategy when network load goes high. This explains why dual-duct rings have better blocking performance but lower network capacity utilization than single-duct rings when network load is more than 65% of the network capacity, and vice versa when network load is below 35%.

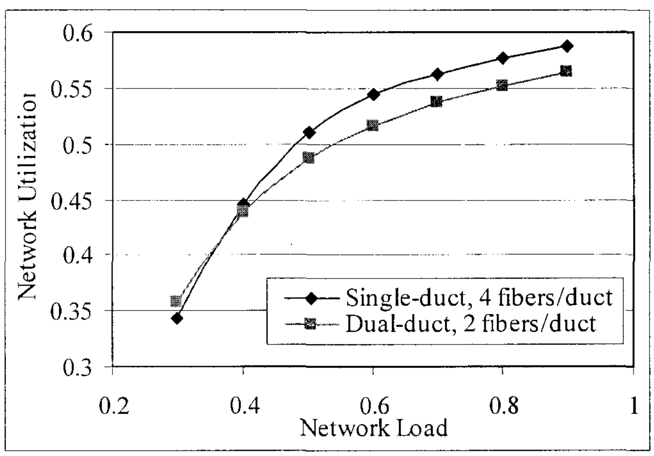
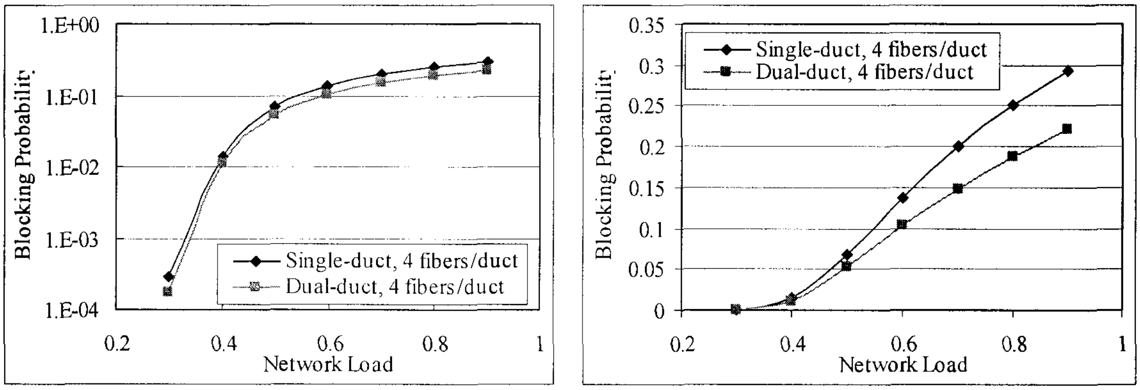


Fig. 6.4. Network capacity utilizations in single- and dual-duct networks with equal network capacity and equal amount of network traffic load.

In Fig. 6.5, dual-duct rings have 4 fibers in each duct whereas single-duct rings have 4 fibers in each duct as well. Hence, dual-duct rings have twice the network capacity of single-duct rings. On the other hand, dual-duct rings are loaded with fourfold the amount of primary traffic load of single-duct rings. Therefore, the two kinds of networks have the same total traffic load. The curves of blocking probabilities in single-and dual-duct rings prove that dual-duct networks outperforms single-duct networks when dual-duct networks have more flexibility in bandwidth allocation with 4 fibers in each duct. In addition, Fig. 6.6 reveals network capacity utilizations for the two kinds of networks to achieve the blocking performances shown in Fig. 6.5. With the comparison of the two figures, it is derived that high blocking results in low capacity utilization.



a) logarithmic scale　　b) linear scale

Fig. 6.5. Blocking probabilities in single- and dual-duct networks, dual-duct networks double the network capacity and fourfold the amount of primary traffic load in single-duct networks.

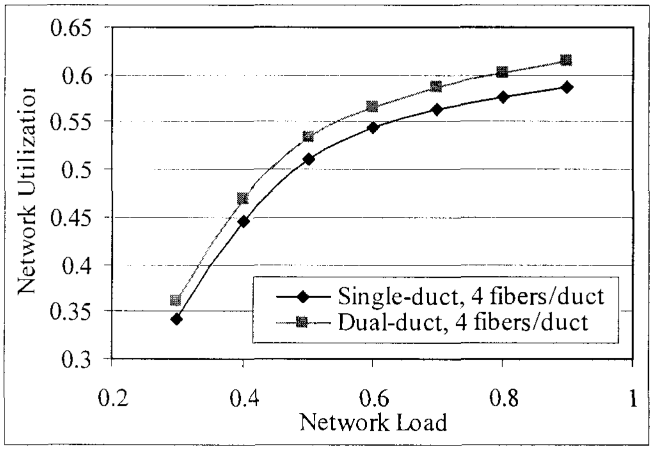


Fig. 6.6. Network capacity utilizations in single- and dual-duct networks, dual-duct networks double the network capacity and fourfold the amount of primary traffic load in single-duct networks.

6.3.3 Availability comparison of single- and dual-duct rings

Availability is the most important survivability measure that is based on probability analysis. It is defined as the probability that a repairable entity is in an operating state [Mika04] [Zhou07]. The study of connection availability has become a practical issue for critical network services in next-generation networks. The availabilities of single- and dual-duct rings, which provide dedicated channel-based protections for critical services, are studied in this section.

In this section, it is assumed that nodes are reliable because of the highly effective redundancy design in node architecture. The availability analysis is therefore focused on link failures. A link is defined here to be a group of fibers in a duct between two adjacent nodes. Suppose that links in networks have equal unavailability U. Then the unavailability of an unprotected connection traveling H hops is $U_c \approx HU$ while $U_c \ll 1$.

In both survivable single- and dual-duct rings, the primary lightpath of each critical connection takes the shortest route. Based on the presupposition, network traffic is evenly distributed in the ring networks. Therefore, the probability that the primary lightpath of a critical connection will travel H hops is

$$P_r(H = h) = 2/(N-1),\ h = 1,2,...(N/2-1),$$

$$P_r(H = h) = 1/(N-1),\ h = N/2,$$

when N is even; or

$$P_r(H = h) = 2/(N-1),\ h = 1,2,...(N-1)/2,$$

when N is odd.

In survivable single-duct rings, the backup lightpath of a critical connection spans N-H hops if the primary lightpath of the critical connection travels H hops based on shortest path routing. The unavailability of the primary lightpath is $U_p \approx HU$ since $U_p \ll 1$, while the unavailability of the backup lightpath is $U_b \approx (N-H)U$ since $U_b \ll 1$. Then the unavailability of the critical connection is $U_c = U_p U_b \approx H(N-H)U^2$, and thus, the availability of the connection is $A_c \approx 1 - H(N-H)U^2$. For critical services in survivable single-duct rings, the overall connection availability A_o^s is

$$A_o^s \approx \frac{2}{N-1}\left[\sum_{h=1}^{N/2-1}[1-h(N-h)U^2]\right] + \frac{1}{N-1}\left[1-\frac{1}{4}N^2U^2\right],$$

when N is even or

$$A_o^s \approx \frac{2}{N-1}\left[\sum_{h=1}^{(N-1)/2}[1-h(N-h)U^2]\right],$$

when N is odd.

In survivable dual-duct rings, both primary and backup lightpaths of a critical connection spans the same number of hops, supposed to be H. The unavailability of the primary lightpath is the same as the unavailability of the backup lightpath: $U_p = U_b \approx HU$ since $U_p \ll 1$ and $U_b \ll 1$. Then the unavailability of the connection is $U_c = U_p U_b \approx H^2 U^2$, and thus, the availability of the connection is $A_c \approx 1 - H^2 U^2$. For critical connections in survivable dual-duct rings, the overall availability A_o^d is

$$A_o^d \approx \frac{2}{N-1}\left[\sum_{h=1}^{N/2-1}[1-h^2U^2]\right]+\frac{1}{N-1}\left[1-\frac{1}{4}N^2U^2\right],$$

when N is even or

$$A_o^d \approx \frac{2}{N-1}\left[\sum_{h=1}^{(N-1)/2}[1-h^2U^2]\right],$$

when N is odd. Therefore, survivable dual-duct rings outperform survivable single-duct rings in connection availability at the amount of $A_o^d - A_o^s \approx \frac{N(N^2-4)}{12(N-1)}U^2$ when N is even, or $A_o^d - A_o^s \approx \frac{N(N+1)}{12}U^2$ when N is odd.

Node failures may cause some problems for dual-duct ring protection with proactive span switching strategy, which utilizes the same transit nodes in both primary and backup lightpaths for critical services. However, this problem is handled by supplementary reactive ring switching strategy in survivable dual-duct ring networks with some more recovery time. Nevertheless, the connection availability of dual-duct rings is higher than that of the single-duct rings because in average, the number of the transit nodes and links along the route of backup path in dual-duct rings is lesser than that in single-duct rings. Network design

6.4 Concluding remarks

The optical survivability of agile all-optical networks is designed with reference to the protection and restoration technologies from SONET/SDH. Based on the characteristics of network services, optical survivability of agile all-optical ring networks is proposed to be based on channel protections in order to achieve differentiated QoS for network users. As distributed-controlled networks, optical survivability of agile all-optical metro ring networks require less degree of coordination between network nodes because of the simplicity of the topology.

In single-duct bidirectional ring networks, link-disjoint backup lightpaths are intrinsically much longer than primary lightpaths, which increases the chances to have a critical connection request be blocked because of the wavelength continuity constraint and the slotting constraint. Rearrangement is therefore proposed to rearrange backup lightpaths in order to accommodate new connections. Three lightpath rearrangement approaches are presented and the simulation results shows that the approach of ordering backup lightpath rearrangement according to both timeslot usage and connection hop count wins. However, rearrangement cannot solve the problem of network resource consumption for the long backup lightpaths in survivable single-duct ring networks.

Dual-duct bidirectional ring networks are therefore proposed with survivability strategy of proactive span switching and supplementary reactive ring switching. Both mathematical and simulation analysis shows that survivable dual-duct rings have lower redundancy rate and utilize network capacity for backup purposes more efficiently than survivable single-duct rings. By assuming guaranteed reliability of network nodes with high redundancy design, connection availabilities are investigated for single- and dual-duct rings. Focused on link failures, connection availability of dual-duct rings is higher than that of single-duct rings.

Ch. 7 Conclusion

This thesis covers several aspects in designing a fast and smart control mechanism for the connection operations management in agile all-optical networks. By using analytical and simulation models, the proposed approaches are evaluated under different network configurations, network conditions, and approach parameter settings. In this chapter, the main results are summarized and some suggestions are given for future work.

7.1 Summary

Next-generation all-optical networks will be characterized by agility and intelligent control. Agility indicates the ability to reconfigure networks to provide rapid bandwidth allocation for flexible bandwidth requirements at an appropriate channel granularity. Intelligent control aims to manage next-generation all-optical networks to serve differentiated QoS bandwidth requirements in the ubiquitous and pervasive communication environment.

This thesis focuses on the traffic diversity in metropolitan ("metro") networks and has investigated the intelligent traffic control issues in agile all-optical networks that provide dynamic and flexible QoS bandwidth services to end users. This work has based the research on an extensive review of state-of-art achievements and foreseeing technologies. It has been implemented in a service-oriented manner to develop networks aiming to accommodate newly emerging and potential user traffic. The ring is chosen to be the topology of the next-generation metro optical networks in order to achieve control simplicity, network survivability and cost effectiveness. This thesis has covered the intelligent control of *bandwidth allocation*, *signaling and reservation*, and *network protection and restoration* in the control plane of agile all-optical metro ring networks.

The problem of *bandwidth allocation* for user traffic in agile all-optical networks has two new features. From network service perspective, the potential network traffic is fast-changing with flexible bandwidth requirements. From the perspective of network infrastructure, time division multiplexing in the optical domain is applied on wavelength channels to permit bandwidth virtualization, to provide adequate granularity, and to enable flexible bandwidths ranging from sub-wavelength to super-wavelength for network services. With bandwidth virtualization, the problem of bandwidth allocation for dynamic and flexible traffic demands in agile all-optical metro ring networks is the problem of Dynamic Routing, Wavelength and Timeslot Assignment (DRWTA).

Considering the characteristics of ring topology, the residual Wavelength and Timeslot Assignment (WTA) algorithm has been proposed to accommodate dynamic and flexible bandwidth requirements in single-fiber networks. The algorithm makes use of the wavelength continuity constraint and slotting constraint to pack traffic together, and aims to minimize network blocking probability. By incorporating the concept of dynamic programming technique, which is a recursive approach in solving time-related optimization problems, the algorithm is capable of providing rapid bandwidth allocation. Through the verification of simulation, it has been shown that the proposed residual WTA algorithm outperforms the Random WTA algorithm and the First-Fit WTA algorithm, which apply the well-know Random rule or First-Fit rule into the wavelength assignment and the timeslot assignment.

Noticing that the simulation tool is more expensive than mathematical modeling, a quasi-analytical model has been proposed to facilitate the derivation of traffic blocking probability in single-fiber metro ring networks. The model is based on the Random WTA algorithm to decouple the problems of the wavelength assignment and the timeslot assignment, and to decrease the correlation in flexible bandwidth allocation. The accuracy of the quasi-analytical model has been verified through simulation. With the model, the blocking analysis of single-fiber metro ring networks can be achieved in a fast and cost-effective way.

In multi-fiber ring networks, the indexed fiber designation scheme was shown to reduce traffic blocking. Compared with the Fiber, Wavelength and Timeslot Assignment (FWTA) algorithms applying the LL rule, which is a well-known rule for bandwidth allocation in wavelength-routed multi-fiber WDM networks, the proposed indexed fiber designation scheme has shown outstanding performance in network blocking when it works with the packing FWTA heuristics (First-Fit and/or Most-Used on shortest path). The reason behind this is the additional level of assignment, timeslot assignment, and the additional level of constraint, slotting constraint in the problem of bandwidth virtualization in wavelength-and-timeslot-routed multi-fiber WDM-TDM networks. Furthermore, the solution of timeslot assignment here aims to confine one demand on one wavelength (for sub-wavelength data flows) or several wavelengths (for super-wavelength data flows), considering the limitation of all-optical channel add/drop realization. The LL rule cannot efficiently solve the problem of bandwidth virtualization where wavelength continuity constraint and slotting constraint apply. On the other hand, the proposed indexed fiber designation scheme increases traffic load correlation and thus enhances the packing effects in traffic accommodation in ring networks by introducing fiber continuity constraint into the FWTA problem. Verified through simulation, the benefit that comes from the scheme in network blocking performance (packing effects) outweighs the limitation it introduces (fiber continuity constraint) in ring network environment. The best blocking performance is achieved by closely packing existing traffic together in fiber, wavelength and timeslot space of ring networks and leaving more global idle capacity for further incoming traffic demands. Additionally, the proposed quasi-analytical model is capable of deriving the blocking performance of multi-fiber metro ring networks where the bandwidth allocation approach is the indexed fiber designation scheme combined with the Random fiber, wavelength and timeslots assignment algorithm.

Signaling and reservation schemes are traffic control protocols that handle network information exchange and network reconfiguration in order to accommodate user traffic according to the decisions of bandwidth allocation for connections. The kind of signaling and reservation protocols that has global link-state information awareness on all network nodes is a common approach in literature where periodic update and triggered update are two classes of schemes as the ways of network-wide link-state information exchange. These two information exchange schemes introduce stale link-state information in bandwidth allocation calculation because of non-instant link-state exchange.

Based on the identification of the characteristics of agile all-optical networks and the user traffic patterns in the networks, two signaling and reservation protocols have been defined for the connection operation in agile all-optical metro rings with either periodic update scheme or triggered update scheme. The link-state exchange in the periodic link-state update protocol happens with a constant refresh period while the link-state exchange in the triggered link-state update protocol takes place when more than a certain amount of link states change their statuses. The frequency of the network-wide link-state information exchange in the protocols determines the staleness of global link-state information and the amount of control overhead. Compared with periodic link-state update protocol that has a predictable amount of control traffic, triggered link-state update is link-state change oriented and provides more accurate link-state information for bandwidth allocation calculation. Shown from the simulation results, triggered link-state update protocol with a medium amount of network-wide link-state exchange outperforms periodic link-state update protocol with extremely large amount of the control overhead.

With the triggered link-state update protocol and the adaptive bandwidth allocation, where the bandwidth allocation algorithm is adapted from the Random Wavelength and Timeslot Assignment (WTA) to the First-Fit WTA with the increase in network load to achieve the lowest network blocking probability, network blocking performance is still degraded because of stale link-state information. The degradation is especially large in light-load network conditions where blocking is primarily caused by incorrect link-state information. On the other hand, the gain from the control overhead of network-wide information exchange is limited because of the ring topology of agile all-optical networks where adaptive routing, which is a main objective of global link-state exchange, is not applicable. Therefore, the kind of signaling and reservation protocol with only local link-state information is chosen here to eliminate the control overhead in network-wide link-state information exchange. Specifically, the backward reservation protocol has been presented against the characteristics of the ring topology and traffic patterns in agile all-optical networks.

The traffic in agile all-optical metro ring networks is highly dynamic so that frequent global link-state update will cause a significant amount of control overhead while infrequent information exchange will result in worse accuracy of global link-state. On the other hand, the objective of the link-state collection is to use the link-state information in the route selection and wavelength and timeslot assignment for the bandwidth allocation of traffic demands. In ring networks, the route selection is based on fixed routing without the involvement of link-state information. Therefore, in networks applying the backward reservation protocol, each node only maintains the state information of its own outgoing links. The link-state information along the routing path of a connection (path link-state information) is collected while a signaling message travels from the source node to the destination node of the connection. Based on the collected path link-state information, the wavelength and timeslot assignment decision is made thereafter. The collected path link-state information may become stale because of propagation delays in networks. However, it has been shown that, in ring networks where the mean service time of connections is greater than several seconds, the kind of protocol with only local link-state information, the backward reservation protocol, has better blocking performance than the kind of protocols with global information available, the periodic link-state update protocol and the triggered link-state update protocol, adding a slight amount of node processing on the intermediate nodes of connections and eliminating a significant amount of node processing and signaling bandwidth in global link-state exchange.

Network protection and restoration is an essential functionality in networks to maintain the continuity of critical services in which optical layer survivability plays an important role because of its speed, simplicity, and efficiency in detecting and handling certain types of network faults, such as fiber cuts and node failures. According to the features of network services, the basic protection and restoration scheme, which applies channel-based protection for critical traffic and takes protection bandwidth reuse for best-effort traffic, is chosen for survivable agile all-optical networks. With this scheme, survivable agile all-optical networks can provide differentiated QoS for network traffic demands.

Based on the basic protection scheme, the survivability strategy for single-duct ring networks has been defined where a critical connection is accommodated into a network only when both primary and backup lightpaths can be set up simultaneously. With this strategy, the backup lightpath of a critical demand takes a much longer route than the primary lightpath of the demand since there are two and only two link-disjoint routes in survivable agile all-optical rings. The long backup lightpath makes the accommodation of critical network services become more difficult because of the wavelength continuity constraint and slotting constraint. Therefore, rearrangement is incorporated aiming to accommodate new traffic through the rearrangement of backup lightpaths. The backup lightpath rearrangement is a kind of optimization problem. In order to serve the fast-changing traffic in a timely manner, some heuristics have been proposed for backup lightpath rearrangement. It has been shown that the rearrangement of backup lightpaths can somewhat decrease network blocking probability. The best blocking performance is achieved by the heuristic that is designed with the consideration of the two dimensional requirements of backup lightpaths, the number of hop counts and the number of timeslots, in the rearrangement calculation in order to use available network resources effectively.

In survivable single-duct rings, backup lightpaths always take a much longer route than primary lightpaths, which results in inefficient network resource utilization and signal degradation on long lightpaths in all-optical switching. The architecture of survivable dual-duct bidirectional rings is therefore adopted with survivability strategy of proactive span switching and supplementary reactive ring switching proposed here. Both mathematical analysis and simulation modeling have revealed that survivable dual-duct rings have lower redundancy rate and utilize network capacity for backup purposes more efficiently than survivable single-duct rings. Since network nodes are commonly designed with high redundancy, the connection availability analysis here focuses on link failures. It has been shown that the connection availability of survivable dual-duct rings is higher than that of survivable single-duct rings.

In conclusion, this thesis has shown the results of intelligent traffic control in bandwidth-virtualization-enabled agile all-optical networks from the aspects of bandwidth allocation, signaling and reservation, and network protection and restoration.

7.2 Suggestions for future work

There are a number of potential topics that could be valuable for further work:

Bandwidth allocation

- Bandwidth allocation for multicast traffic: IP traffic is the dominant form in network service prospective and multicast is an important form of IP connections. It is a significant improvement if an effective way could be found to accommodate multicast traffic in agile all-optical networks. Bandwidth allocation for multicast traffic may be realized by simultaneously setting up two lightpaths in two directions with each traveling half circle of ring networks, and intelligently dropping a portion of the multicast signal at each node that is being casted. There are two primary technical difficulties here. One is that how to make network nodes to have the intelligence to distinguish regular lightpaths and multicast lightpaths. The other is how to guarantee the signal quality when multicast signals are dropped and amplified at each node being casted. If all-optical realization cannot support this configuration, OEO conversion and signal regeneration may be needed to maintain the quality of multicast signals.

- Bandwidth allocation for mesh networks: the mesh network topology is intrinsically compatible with the characteristics of Ethernet so that fully meshed all-optical networks will be an even better supporting layer for upper layers in next-generation Ethernet-based communication network infrastructure. In addition, by incorporating intelligent control mechanism, fully meshed all-optical networks not only have the ability to survive multiple failures, but also will enable new network services. The mesh network topology is therefore a trend for dynamic optical networks. Network synchronization is an issue in mesh all-optical networks. Mesh networks contain loops. To apply WDM-TDM multiplexing in mesh networks, the propagation time around each loop must be an integer number of slots. Otherwise, either a programmable transparent optical delay line is needed or OEO conversion combined with electronic memories is required.

Signaling and reservation

- Protection signaling: protection signaling includes fault detection, localization and recovery, and restoration to primary paths when primary paths return to work. One issue in optical network protection signaling is interworking with lower layers to promptly acquire the outage and recovery information and to quickly identify the outage and recovery location. Another issue, which is correlated with the first one, is that how to guarantee the restoration of protected services to be within 50 ms time frame in the optical layer.

- Signaling system survivability: network signaling system controls the restoration of critical network services from network failures and is thus essential for network survivability. Therefore, signaling system itself must have the ability to survive network failures. The possible solution for survivable signaling system is in-band signaling supplemented with out-band signaling. In-band signaling consumes network bandwidth but provides rapid responses to network failures. Out-band signaling is cheaper and can act as a supplementary signaling system, providing signaling service during the failure of in-band signaling system. One issue behind this is that the cooperation of the two systems.

Optical survivability

- Disaster avoidance strategy: disaster avoidance strategy attracts more and more attentions when network capacity expands quickly. The strategy needs to coordinate protection activities in multiple layers of communication networks and to organize multi-layer network protection efficiently. The strategy includes the identification of all kinds of failures in each layer, the definition of the recovery scheme for each kind of failures, the description of cooperation among network nodes for the fault recovery in each layer, and the designation of coordination between layers in each node.

Overall network design

- Next-generation communication networks should be able to realize self-evolving and self-optimization to adaptive to the pervasive and ubiquitous communication environments. One approach could be setting up an intelligent agent on each node outside of the intelligent control with the layered protocols to overlook the self-evolving and self-optimization issues by introducing the artificial intelligence and expert knowledge databases into each node.

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Appendix 1. Program Codes of Simulation Models

The simulation models built to verify the algorithms and protocols in this thesis were written in C++ language and compiled with the Microsoft™ Visual C++ compiler as console applications. The names and functions of the simulation models are listed below:

1. residual.cpp, random.cpp: the residual wavelength and timeslot assignment algorithm and the Random wavelength and timeslot assignment algorithm in Section 4.1.3.
2. residual_optm.cpp, first.cpp: the optimized residual wavelength and timeslot assignment algorithm and the First-Fit wavelength and timeslot assignment algorithm in Section 4.1.4.
3. analnM.cpp: the quasi-analytical model in Section 4.2.3
4. mFF.cpp, mFL.cpp, mFM.cpp, mFR.cpp, mLF.cpp, mLL.cpp, mLM.cpp, mLR.cpp, mMF.cpp, mML.cpp, mMM.cpp, mMR.cpp, mRF.cpp, mRL.cpp, mRM.cpp, mRR.cpp,: the 16 fiber, wavelength and timeslot assignment algorithms for multi-fiber ring networks that come from the combinations of the four assignment approaches, First-Fit, Random, Least-Used on shortest path and Most-Used on shortest path in Section 4.3.
5. mLeastL.cpp, mLeastF.cpp: the fiber, wavelength and timeslot assignment algorithms applying the LL rule with Least-Used or with First-Fit in Section 4.4.
6. period_first.cpp, period_random.cpp, period_ranstart.cpp: the periodic link-state update protocol with First-Fit, Random or Random start point wavelength and timeslot assignment in Section 5.1.2.
7. qtrigger_first.cpp, qtrigger_random.cpp: the triggered link-state update protocol with First-Fit or Random wavelength and timeslot assignment in Section 5.1.4.
8. rback_first.cpp, rback_random.cpp: the backward reservation protocol with First-Fit or Random wavelength and timeslot assignment in Section 5.2.2
9. protect_n.cpp: critical network service protection in single-fiber rings without backup lightpath rearrangement in Section 6.2.2.
10. protect_y1.cpp, protect_y2.cpp: critical network service protection in single-fiber rings with backup lightpath rearrangement for Most-Used rearrangement algorithm

or the rearrangement algorithm considering both the number of hop counts and the number of timeslots in Section 6.2.2.

11. protect_bn.cpp: critical network service protection in dual-fiber rings without backup lightpath rearrangement in Section 6.3.2