國立台灣大學資訊管理研究所碩士論文

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多波長分工網狀網路上訊流匯整及
路由波長分配演算法

A Traffic Grooming, Routing and Wavelength Assignment Algorithm for Optical WDM Mesh Networks

研究生： 施閔元 撰

中華民國 九十三 年 七 月

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本論文係提交國立台灣大學
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于台大資訊管理研究所

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論文摘要

近年來，光通訊網路技術中的多波長分工網路快速成長為被廣泛期許的傳輸標準之一。由於多波長分工網路技術發展，以及光波長的頻寬可高達每秒數十億位元組，使得光網路現有的流量需求常低於單一光波長的全頻寬。許多學者及業界人士正致力於將現有的網路流量以訊流匯整的方式負載於同一光波長上，讓多波長分工網路技術得以充分利用其所帶來之大量頻寬。

目前相關研究大多著重在現有 SONET 的環狀網路架構下，如何最大化由於多波長分工網路上支援多網路流量共同使用同一波長光路徑而提高的網路流量；以及如何降低其網路架構成本。為能有效的利用多波長分工網路所帶來的大量頻寬，本篇論文將研究在一般網狀網路架構下之多波長分工網路訊流匯整問題。在既有的網路流量需求及其他限制條件下，對於網路服務提供者，希望能建立網路設備租用成本最小化的網路。

我們將整個問題仔細地分析並轉換成一個最佳化數學模型，這個數學問題在本質上是一個非線性混和整數規劃問題，問題的本身具有高度的複雜性和困難度。我們採用以拉格蘭日鬆弛法為基礎的方法來處理此一複雜問題。

關鍵詞：多波長分工網路、訊流匯整、路由、波長分配、網路服務提供者、最小成本、最佳化、拉格蘭日鬆弛法、數學規劃。

THESIS ABSTRACT

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A TRAFFIC GROOMING, ROUTING AND WAVELENGTH ASSIGNMENT ALGORITHM FOR OPTICAL WDM MESH NETWORKS

Recently, there has been a growing excitement in the area of optical wavelength division multiplexing (WDM) networks. While a single fiber has a huge bandwidth capacity and a wavelength has over a gigabit per second transmission speed, the traffic demands at speed that are lower than the full wavelength capacity are frequent in the current WDM network. Researchers and optical networking industries are now trying to find a way to support multiple low-speed traffic streams onto a single high-speed wavelength to improve the wavelength channel utilization and to minimize the amount of electronic multiplexing equipment.

The issue of traffic grooming, routing and wavelength assignment in optical WDM networks in this thesis is formulated as a combinatorial optimization problem, of which the objective function is to minimize the total leasing cost for network service provider (NSP) upon the underlying WDM network subject to physical link capacity constraints, wavelength continuity constraints, and wavelength add/drop port constraints. The decision variables in these formulations include traffic demand routing, lightpath in WDM layer routing and wavelength assignment, the number of leasing wavelengths in each fiber link, and the number of leasing add/drop ports in each optical cross-connects switch (OXC) .

The basic approach to the algorithm development for this thesis is Lagrangian relaxation in conjunction with a number of optimization techniques. In computational experiments, the proposed algorithms are evaluated on different network topologies.

Keywords: WDM, Traffic Grooming, Network Planning, Routing, Wavelength Assignment, Network Service Provider, Minimum Cost, Optimization, Lagrangian Relaxation, Mathematical Programming.

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Chapter 1 Introduction

1.1 Background

In the last several years, there has been a growing excitement in the area of optical wavelength division multiplexing (WDM) networks. The process of WDM mechanics is to send multiple light waves (frequencies) across a single optical fiber. Information is carried by each wavelength, which is called a channel. At the receiving end, an optical prism or a similar device is used to separate the frequencies, and information carried by each channel is extracted separately. WDM also can enhance an optical network's capacity without expensive re-cabling and can reduce the cost of network upgrades. Recent optical technology shows that one optical fiber can support over 160 channels, each of which can have a transmission speed of OC– 48 (2.4 Gbps). Furthermore, channel operating at OC-768 (40 Gbps) will be commercially available in the near future.

Current development activities indicate that WDM technology will be deployed mainly in a backbone network for large regions. It has been accepted far and wide optical networks will structure the building blocks for the next generation Internet. WDM technology is to be a promising transport mechanism to accommodate the explosive growth of Internet and telecommunication traffic in wide-area, metro-area, and local-area networks [11].

At beginning, telecommunication companies deployed WDM technology for a fixed point-to-point communication, and the deployment was driven by the increasing demands on bandwidth. WDM is a more cost-effective alternative compared to laying more fiber optics [7].

After significant advances, reconfigurable optical add/drop multiplexers (OADMs) and reconfigurable optical cross-connects switches (OXCs), in optical component technologies are proposed, the switching function of WDM network becomes possible and the routing capacity of the WDM network is more flexible [12].

In Figure 1-1, the architecture of OXCs and OADMs, wavelength routing is defined to be the selective routing of optical signals according to their wavelengths as they travel through the network elements between source and destination without wavelength converters. The importance of OXCs and OADMs is that it allows the WDM network to be reconfigured on a wavelength-by-wavelength basis to optimize traffic, congestion, and network growth.

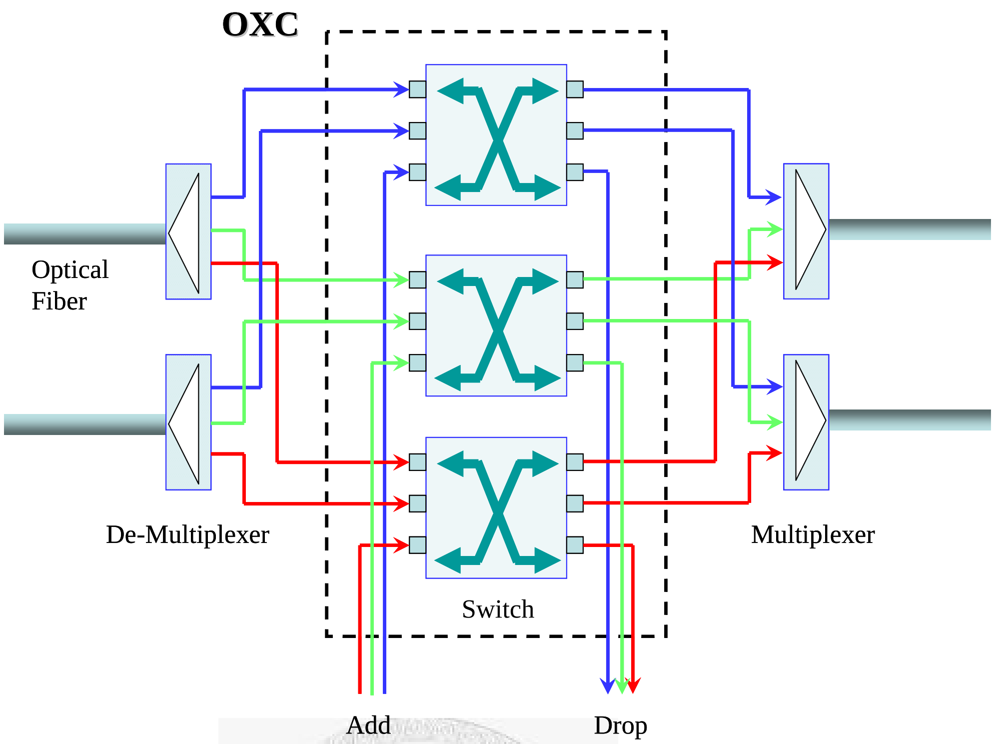

Figure 1-1 Architecture of OXC

A *lightpath* is an all optical channel which may be used to carry circuit-switched traffic, and it may span multiple fiber links. In the absence of wavelength converters, a lightpath would occupy the same wavelength on all fiber links through which it passes and this is called *wavelength continuity constraint*. A lightpath can create logical neighbors out of nodes that may be geographically far apart in the network. Using lightpath communications, a number of lightpaths would be set up on the network in order to embed a *logical topology*. The logical topology, whose vertex is the IP router and whose edge, *logical link*, is made of the lightpaths with the same originating node and terminating node, is overlaid to the physical topology, made of optical fibers and OXCs.

In our thesis, we assume there is no wavelength conversion for each established lightpath, because the O-E-O wavelength conversion slows down the network performance. However, we allow traffic demands being sent through different lightpaths on a single path and use the hop-count constraint to limit the downgrade of performance from the O-E-O conversions. We don't take the all-optical wavelength conversion into consideration in our model since the cost of the conversion is still too high so far.

At the present time, most of the traffic connections in a communication system have smaller bandwidth requirement comparing to the large granularity of the wavelength capacity. With such traffic patterns and characteristics, assigning one wavelength for each connection request could lead to poor bandwidth utilization, and hence link capacity could be greatly under-utilized. Therefore, if there is a way to aggregate the traffic of multiple connections into a single wavelength channel, the wavelength capacity would be highly utilized. Traffic grooming is such a technique that divides a lightpath into multiple time slots and traffic demands can be multiplexed on the same lightpath. It can significantly improve the utilization of bandwidth of wavelength channels. The resulting multi-wavelength time-division multiplexed networks are referred to as WDM-TDM networks or WDM grooming networks [13].

Recent progress in optical switching technology that results in faster switches up to sub-nanosecond switching times, and the introduction of fiber delay lines as time-slot interchangers make all-optical TDM networks potentially feasible in the future. An architectural prototype of a TDM routed node, called time wavelength space router, is presented in [7]. It is capable of routing data in the dimension of time, wavelength, and space in a TDM wavelength-routed network.

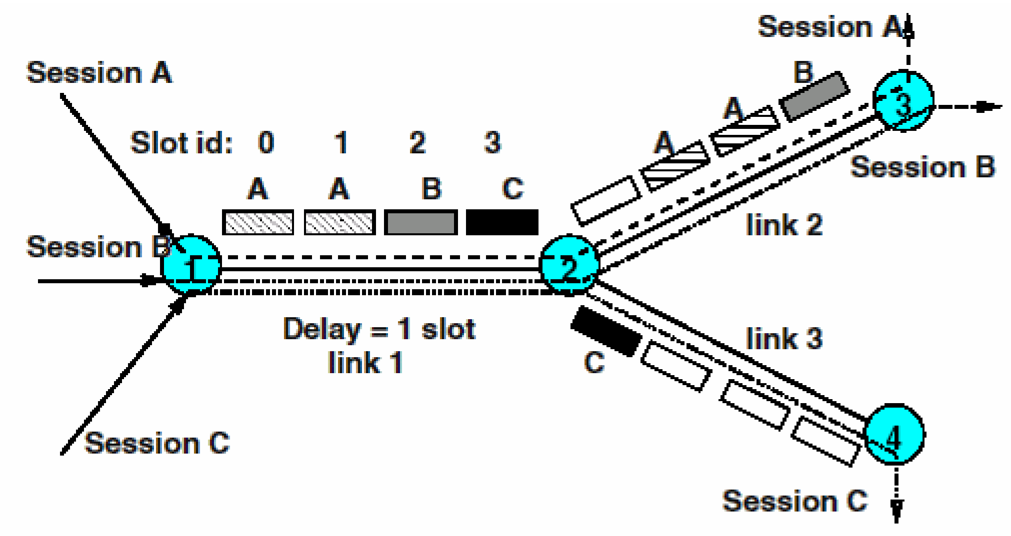

Figure 1-2 Time-slot Allocation for a TDM Wavelength-routed Network

An example showing how the TDM works on WDM networks is illustrated in Figure 1-2 [18]. In the figure, each wavelength is divided into frames, which are composed of four time-slots. Session A's traffic is routed from node 1 to 3 through node 2. It is assigned slots 0 and 1 on link 1; and slots 1 and 2 on link2. The link propagation and node processing delay result in a shifted time-slot allocation, with propagation delay dominating in WANs. The combined link delay is considered to be an integral number of time-slots, with optical synchronizers used to align data to slots. In the example a delay of one slot is assumed for link 1, shifting the allocated slots on link 2 with one slot. Similarly, the time-slot allocations for session B and C can be seen in the figure.

Figure 1-3 shows such an OXC architecture, which has hierarchical switching and multiplexing functionality. Instead of using a separate wavelength switching system and a grooming system, the OXC in Figure 1-3 can directly support low-speed circuits and groom them onto wavelength channels through a grooming fabric (G-Fabric) and built-in transceiver arrays. This kind of OXC is named as wavelength grooming cross connect (WGXC) in [16]. In a network equipped with a WGXC at every node, the grooming fabric and the size of the transceiver array provide another dimension of constraints on the network performance besides the wavelength resource constraint. The transceiver array used in the OXC can be either tunable or fixed. A tunable transceiver can be tuned between different wavelengths so that it can send out or receive an optical signal on any free wavelength in its tuning range. A fixed transceiver can only emit or receiver an optical signals on one wavelength. In our thesis, we use tunable transceiver to each OXC, i.e. only transceivers available can we groom the low speed traffic demands to a lightpath.

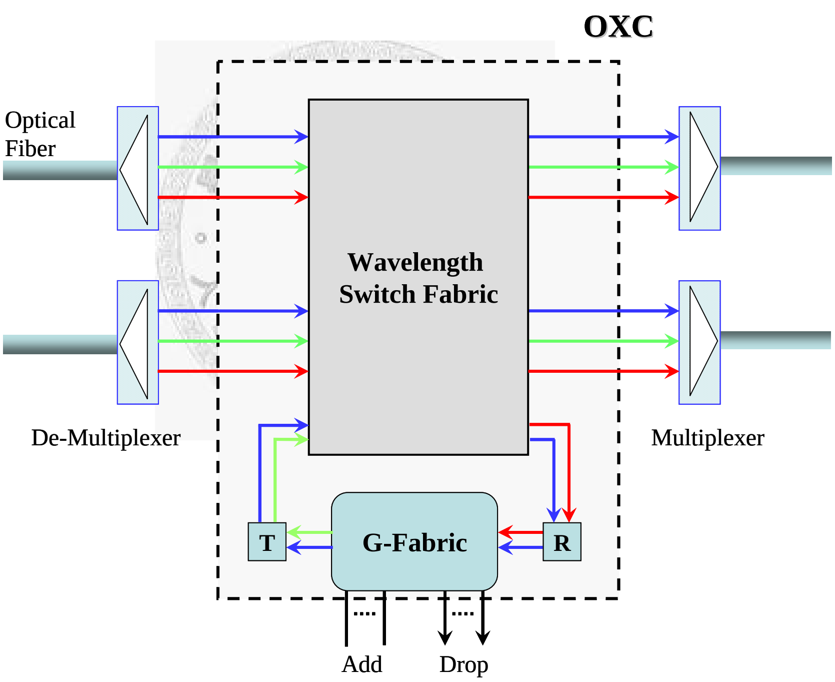

Figure 1-3 OXC with grooming capacity

Figure 1-4 is an illustrative example of traffic grooming in a WDM mesh network. Figure 1-4 (b) shows a simple network with four nodes. We assume that each fiber has two wavelength channels and the capacity per wavelength channel is OC-48 (2.5 Gbps). Each node is assumed to have only one tunable transmitter and receiver which can be tuned to any wavelength. The traffic demand matrix is shown as the following table:

Table 1-1 Traffic Requirement of the Grooming Example

	Origin	Destination	Requirement
Connection 1	C	B	OC-12
Connection 2	B	D	OC-12
Connection 3	C	D	OC-3

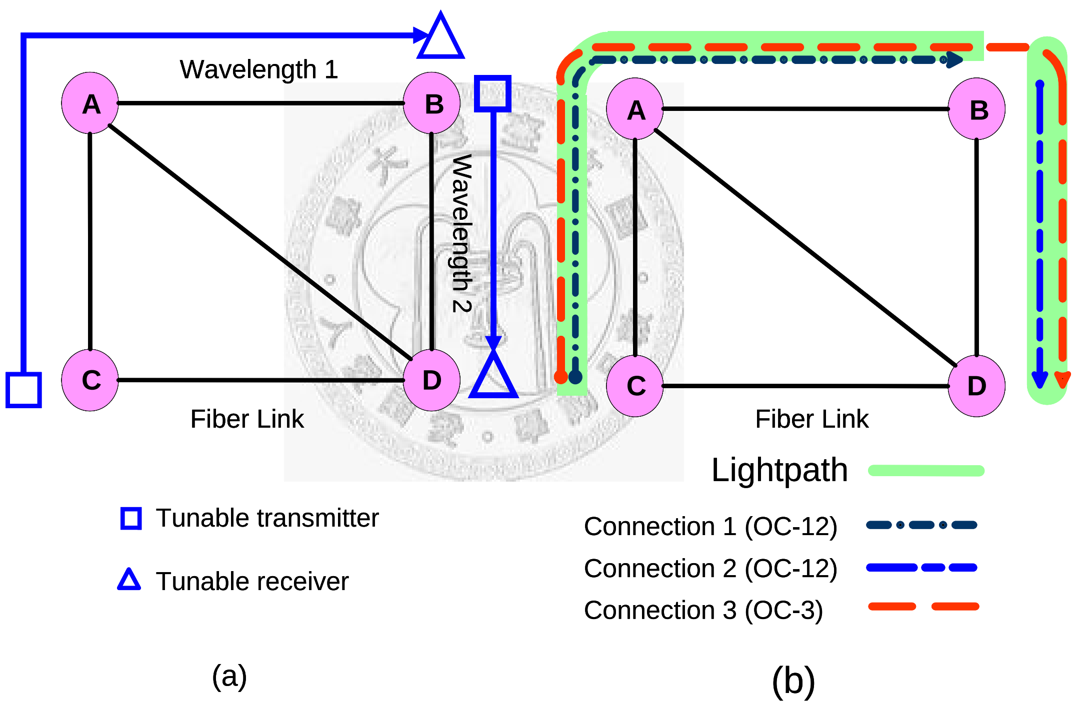

Figure 1-4 Example of Traffic Grooming

In order to satisfy the traffic requirement, two lightpaths are established under the original WDM network without traffic grooming support; however, due to the resource limitation, a direct lightpath between node C and node D cannot be created. And thus, the connection request 3 cannot be fulfilled unless more transceivers are added at each node and available wavelength channels on fibers are increased. On the contrary, with traffic grooming support, the connection 3 can be carried by sharing the free capacity of these two existing lightpaths. The grooming result is illustrated in Figure 1-4 (b).

1.2 Motivation

While a single fiber has a huge bandwidth capacity and a wavelength has over a gigabit per second transmission speed, the traffic demands at rates that are lower than the full wavelength capacity are frequent in the current network. The capacity requirements of the low-rate traffic demand can be different in range from STS-1 (51.84 Mbps or lower) up to full wavelength capacity. Though the capacity of a wavelength channel is high, the bandwidth requirement of a typical connection request can vary from the full wavelength capacity down to STS-1 or lower. To efficiently utilize network resources, sub-wavelength-granularity connections can be groomed onto direct optical transmission lightpaths.

In most previous studies on optical networks, traffic demands are usually assumed to be wavelength demands. In practice, optical networks are typically required to carry a large number of lower rate traffic demands. Therefore, traffic grooming is an important mechanism by which low-rate traffic requests could be assigned to wavelengths in order to improve the wavelength channel utilization and to minimize the amount of electronic multiplexing equipment.

Recently, a significant amount of research has been carried out in this area. However most of the research on traffic grooming has been focused on SONET rings [17][19]. Nevertheless, due to the growth in Internet traffic, an increasing number of networks are being arranged in a general mesh topology. Therefore, there is a need to extend the grooming work to general mesh networks. For improving utilization of wavelength channels over WDM networks in the near future, we will propose a mathematical formulation and an optimization-based algorithm considering the traffic grooming, routing, and wavelength assignment problem over WDM mesh networks.

1.3 Literature Survey

In this section, we survey traffic grooming problems in different WDM network topologies. Then, Lagrangian relaxation method is briefly introduced.

1.3.1 Introduction to Traffic Grooming in the WDM Networks

The transmission capacity of a link in today's networks has increased significantly due to WDM technology. The network performance is now mainly limited by the processing capability of the network elements, which are mainly electronic. By efficiently grooming low-speed traffic demands onto high-capacity optical channels, it is possible to minimize this electronic processing and eventually increase the network performance. Traffic grooming is an emerging topic that has been gaining more research and commercial attention. Most research on traffic grooming is mainly based on the ring network topology. Only a few papers take the mesh network into account. We will investigate the topic of traffic grooming either in the WDM ring networks or in the WDM mesh networks.

Studying about traffic grooming on WDM networks is trying to balance the trade-off between the degree of virtual connectivity and the increase in network cost due to the introduction of expensive active components, for example optical transceivers or electronic switches. And the objectives can be summarized to minimize the following:

1) Total number of lightpaths

2) Total number of optical transceivers

3) Total amount of electronic switching

4) Total number of wavelengths used

5) Maximum number of lightpaths at a node

In our model, we will solve the traffic grooming problem from another aspect. We play the Network Service Provider (NSP), providing end-to-end traffic service to customer, but we must lease the equipments of WDM network from Network Provider (NP). Hence, our objective is to minimum the leasing cost of equipments of network leased from NP.

1.3.2 Traffic Grooming in the Ring Networks

The study in [5] concentrates on the SONET architecture. One of the important features of this study is a description of the relevant SONET components and a detailed const model that accounts for these network components. The authors then abstract a mathematical model of the ring network they consider, in which they focus on the number of SONET ADMs as the objective to be minimized. They also provide an example to show that an integrated design approach performs better than the two-step approach in which the virtual topology subproblem and the traffic routing subproblem are decoupled.

In [17], a heuristic based on simulated annealing approach is applied to the problem. A WDM ring is considered, and the objective is to minimize the number of ADMs. Two cases are considered: in one (single-hop), each traffic component has to be carried on just one lightpath, in a single logical hop from source to destination. In the other (multi-hop), each traffic component is terminated exactly once between source and destination, at the hub node (which is assumed to have full SONET cross-connect capabilities). However, the formulations do not exactly implement the single-hop lightpaths; rather, a single-hop connection may be optically terminated at several intermediate nodes that are source or destination nodes for other traffic components sharing the same wavelength.

1.3.3 Traffic Grooming in the Mesh Networks

The problem of traffic grooming to reduce the number of transceivers for general topologies is considered in [8]. All costs except the cost of transceivers are neglected. The authors concentrated on the topology subproblem integrated with the routing subproblem. By assuming that the number of physical links available between neighboring nodes is large enough, the number of wavelengths in the system is not important, and hence, the RWA problem is neglected.

An interesting intuitive observation is pointed out that minimizing endpoints for a given traffic is closely related to maximizing traffic for a given amount of endpoint equipment. This notion is formalized into the key concept of a precise duality, and thus it is shown that the transceiver minimization problem is equivalent to a commodity flow problem. However, the duality is precise only under the assumption that the RWA problem can always be solved and the ability to carry traffic is limited only by available network capacity. In other words, the grooming granularity has no effect. Based on this, a heuristic algorithm is presented that involves starting with an initial topology and successively deleting lightpaths after rerouting the traffic they carry. The computational experiments show that the algorithm does not give the optimal solutions.

J. Q. Hu [6] described the grooming program as a GRWA problem. GRWA means traffic grooming, routing, and wavelength assignment. The author first formulates the GRWA problem as a integer linear programming problem and then, proposes a decomposition method that divides the GRWA problem into two smaller problems: the traffic grooming and routing problem and the wavelength assignment problem, which can then be solved much more efficiently. However, the solution is only a near optimal solution for the original GRWA problem. The author provides that under some sufficient conditions, the decomposition method did give an optimal solution.

The GRWA problem is divided into the traffic grooming and routing (GR) problem, and the wavelength assignment (WA) problem. The GR problem is a smaller ILP problem, and by relaxing some of its integer constraints, the computational efficiency is significantly improved.

In [20], traffic grooming problem is formulated as an Integer Linear Program (ILP) optimization problem. The objective is to maximize network throughput for given static traffic demand, which is defined by the amount of traffic demands that are actually accepted, subject to network resource constraints. In other words, the model does not necessarily serve all the given traffic requirements. As a consequence, some problem instances, which may be not feasible for models that are constrained to serve all traffic requests, may be feasible here. It is somewhat like those models associated with dynamic traffic scenarios.

The authors assume that the common bifurcation is not allowed, and require the data traffic on a connection request always to be routed by the same route. In addition, unlimited mux/demux capability on each node is assumed. This might underestimate the total cost or overestimate the network resources.

Since RWA optimization problem was proved as NP-hard, it is easy to see that the traffic grooming problem in a mesh network is also a NP-hard problem. The authors use a small network topology as an example for obtaining ILP result. As expected, the multi-hop case leads to higher throughput than the single-hop case. However, fast heuristic approaches are needed for a large network or for a dynamic traffic pattern.

In [9], the routes for the traffic demands are assumed to be given already. The author tries to modify a grooming factor g, to find an optimal wavelength assignment and grooming such that the number of wavelengths required in the network is minimized. In addition, the lower-rate traffic demands are assumed to be at the same rate. Though this is not true in reality but it simplifies the procedure of modifying the grooming factor. A heuristic approximation algorithm based on binary search and the LP relaxation of integer linear programming is proposed. According to the simulation results, if the grooming factor g is small, the decrease of wavelengths is faster than the case where g is large.

1.3.4 Introduction to Lagrangian Relaxation Method

In the 1970s, Lagrangian relaxation methods were used in scheduling and solving general integer programming problems [3][4]. Lagrangian relaxation can provide proper solutions for those problems. It is a flexible solution approach. In fact, it has become one of the best tools for solving optimization problems such as integer programming, linear programming combinatorial optimization, and non-linear programming. Lagrangian relaxation has several advantages, for example, Lagrangian relaxation could decompose complex mathematical models in many different ways into some stand-alone subproblems. Then, we can optimally solve the subproblems using any proper algorithm.

Lagrangian relaxation lets us to find out the boundary of our objective function, so we can use it to implement heuristic solutions for getting feasible solutions. Lagrangian relaxation is a flexible solution strategy that permits modelers to exploit the underlying structure in any optimization problem by relaxing complicating constraints. This method permits us to "pull apart" models by removing constraints and place them in the objective function with associated Lagrangian multipliers. The optimal value of the relaxed problem is always a lower bound (for minimization problems) on the objective function value of the problem.

To obtain the best lower bound, we need to choose a minimization multiplier so that the optimal value of the Lagrangian subproblem is as large as possible. We can solve the Lagrangian multiplier problem in a variety of ways.

The subgradient optimization technique is the most popular technique for solving Lagrangian multipliers problems.

1.4 Proposed Approach

We model the problem as an optimization problem. The problems are integer linear mathematical programming problems. We apply the Lagrangian relaxation method and the subgradient method to solve the problem. As we expected, the problem is by nature highly complicated and difficult.

To the best of our knowledge, the propose approach is the first attempt to consider the traffic grooming mechanism with the viewpoint of NSP. We then apply the Lagrange relaxation method and the subgradient method to solve the problem.

Chapter 2 Problem Formulation

2.1 Problem Description

In this chapter, we want to provide a well formulated model to describe the grooming problem. And we take the standpoint from a network service provider. While the network service provider serve all the end-to-end traffic requests in the WDM network, the network service provider has to decide how many network equipments should be leased from the network provider upon the physical link capacity constraints, wavelength continuity constraints, and wavelength add/drop port constraints. The problem we modeled is to minimum the total leasing cost with respect to the charges for leasing wavelengths per fiber link and the charges for leasing add/drop ports per OXC.

Table 2-1 Problem Assumption

Problem assumptions: 1. The network is a single-fiber irregular network. 2. Each OXC has grooming capability. This means that the network node can multiplex as many low-speed traffic streams to a lightpath as needed, as long as the aggregated traffic does not exceed the bandwidth capacity. 3. The OXCs used in the optical network is lack of wavelength conversion capacity. It means that a lightpath connection must be set up on the same wavelength channel if it traverses through several logic links. 4. Wavelength continuity constraint applies. 5. Cost to lease the network, including add/drop ports per OXC and wavelengths per fiber link. 6. Multi-hop lightpaths request is acceptable. This means that a connection request can traverse multiple lightpaths before it reaches the destination. But we take the hop count distance constraint as a QoS requirement in the model into account. The QoS requirement is satisfied by the hop distance in terms of number of logical links pass for each connection request.

Table 2-2 Problem Description

Given: 1. The optical layer topology. 2. The number of wavelengths available per fiber link. 3. The wavelength capacity. 4. The number of add/drop available per OXC. 5. The cost function to lease wavelengths per fiber link.

6. The cost function to lease add/drop ports per OXC.

Objective:

To minimize the total leasing cost in the WDM network.

Subject to:

1. Capacity constraints of components in the WDM network.
2. Single logical path routing constraint for each traffic request.
3. QoS constraint guaranteed by limiting the maximum hop distance for each traffic request in the network.
4. Wavelength continuity constraint.

2.2 Notation

Table 2-3 Notations of Given Parameters

Given Parameters	
Notation	**Description**
N	The set of nodes.
L	The set of logical links.
K	The set of fiber links.
W	The set of O-D pairs.
P_w	The set of candidate logical paths for O-D pair *w*.
$\delta_{p,l}$	1 if logical link *l* is on the logical path *p*; 0 otherwise.
θ	The limited number of hop count for each logical path.
λ_w^i	Traffic requirement for the *i-th* request of O-D pair *w*. And the value can be any of OC-1, OC-3, OC-12, and OC-48.

B	Bandwidth Capacity per channel.
Q_l	The set of candidate lightpaths for logical link *l*.
T_n	The set of candidate outgoing lightpaths from node *n*.
R_n	The set of candidate incoming lightpaths to node *n*.
$s(l)$	The source node of virtual link *l*.
$d(l)$	The destination node of virtual link *l*.
J	The number of channels per fiber link.
A_n	The set of add ports on node *n*.
D_n	The set of drop ports on node *n*.
$\psi_k(f_k)$	The cost to use fiber link *k*, which is function of fiber link *k*.
$\psi_{nt}(a_n)$	The cost to use the add ports on node *n*, which is function of add ports on node *n*.
$\psi_{nr}(d_n)$	The cost to use the drop ports on node *n*, which is function of drop ports on node *n*.
σ_{qk}	1 if lightpath *p* travels through fiber link *k*; 0 otherwise.

Table 2-4 Notations of Decision Variables

Decision Variables	
Notation	**Description**
x_p^i	1 if the *i-th* traffic request of the specific O-D pair uses logical path *p* in the logical network; 0 otherwise.
y_{qj}	1 if wavelength *j* is assigned to lightpath *q* in the physical network; 0 otherwise.
f_k	The number of wavelengths (channels) leased in the fiber link

	k.
a_n	The number of add ports leased on node n.
d_n	The number of drop ports leased on node n.

2.3 Problem Formulation

Objective function:

$$Z_{IP} = \min \sum_{k\in K}\psi_k(F_k) + \sum_{n\in N}\psi_{nt}(a_n) + \sum_{n\in N}\psi_{nr}(d_n) \quad \text{(IP)}$$

Subject to:

$$\sum_{p\in P_w}\sum_{i\in I_w} x_p^i = 1 \qquad \forall w\in W \quad (1)$$

$$\sum_{p\in P_w}\sum_{l\in L} x_p^i \delta_{pl} \le \theta \qquad \forall i\in I_w, w\in W \quad (2)$$

$$x_p^i = 1 \text{ or } 0 \qquad \forall i\in I_w, p\in P_w, w\in W \quad (3)$$

$$\sum_{w\in W}\sum_{p\in P_w}\sum_{i\in I_w} x_p^i \lambda_w^i \delta_{pl} \le \sum_{q\in Q_l}\sum_{j\in J} y_{qj} B \qquad \forall l\in L \quad (4)$$

$$\sum_{l\in L}\sum_{q\in Q_l} y_{qj}\sigma_{qk} \le 1 \qquad \forall k\in K, j\in J \quad (5)$$

$$\sum_{j\in J} y_{qj} \le 1 \qquad \forall q\in Q_l, l\in L \quad (6)$$

$$y_{qj} = 1 \text{ or } 0 \qquad \forall q\in Q_l, l\in L, j\in J \quad (7)$$

$$\sum_{l\in L}\sum_{q\in Q_l}\sum_{j\in J} y_{qj}\sigma_{qk} \le f_k \qquad \forall k\in K \quad (8)$$

$$f_k \in \{0,1,2,\dots,|J|\} \qquad \forall k\in K \quad (9)$$

$$\sum_{q\in T_n}\sum_{j\in J} y_{qj} \le a_n \qquad \forall n\in N \quad (10)$$

$$a_n \in \{0,1,2,\dots,|A_n|\} \qquad \forall n\in N \quad (11)$$

$$\sum_{q\in R_n}\sum_{j\in J} y_{qj} \le d_n \qquad \forall n\in N \quad (12)$$

$$d_n \quad \in \quad \{0,1,2,...,|D_n|\} \qquad \forall n \in N \qquad (13)$$

$$\sum_{q \in Q_l} y_{qj} \sigma_{qk} \quad \leq \quad 1 \qquad \forall k \in K, j \in J, l \in L \qquad (14)$$

The object function represents to minimize the total leasing cost in the WDM network at the viewpoint of the network service provider.

Constraint (1) and (3): All the traffic requests in the same O-D pair used the same exactly one logical path.

Constraint (2): The hop-count number of logical path for each traffic demand is within the hop-count limitations as defined.

Constraint (4): The bandwidth should satisfy the total traffic it carries for each logical link.

Constraint (5), (6) and (7): Ensure every wavelength in each physical link will used at most by one lightpath. And keep the wavelength continuality constraint.

Constraint (8) and (9): The number of leasing wavelengths in a certain fiber link should not exceed the number of wavelengths allocated in it.

Constraint (10) and (11): The number of leasing transmitters on a certain OXC should not exceed the number of transmitters allocated on it.

Constraint (12) and (13): The total number of leasing receivers in a certain fiber link should not exceed the number of receivers allocated on it.

Constraint (14) is a redundant constraint in order to solve the problem more easily.

Chapter 3 Problem Formulation

3.1 Lagrangian Relaxation

By using the Lagrangian relaxation method, we can transform the primal problem (IP) into the following Lagrangian relaxation problem (LR) where constrains (IP.4), (IP.5), (IP.8), (IP.10), and (IP.12) are relaxed.

With a vector of non-negative Lagrangian multipliers, a Lagrangian relaxation problem of IP1 is given below.

Optimization problem (LR):

$$
\begin{aligned}
Z_D(\mu_1,\mu_2,\mu_3,\mu_4,\mu_5,\mu_6) = \min & \sum_{k\in K}\psi\left(F_k\right)+\sum_{n\in N}\psi_{nt}\left(a_n\right)+\sum_{n\in N}\psi_{nr}\left(d_n\right)+ \\
& \sum_{l\in L}\mu_1^l\left(\sum_{w\in W}\sum_{p\in P_w}\sum_{i\in I_w}x_p^i\lambda_w^i\delta_{pl}-\sum_{q\in Q_l}\sum_{j\in J}y_{qj}B\right)+ \\
& \sum_{k\in K}\sum_{j\in J}\mu_2^{kj}\left(\sum_{l\in L}\sum_{q\in Q_l}y_{qj}\sigma_{qk}-1\right)+\sum_{k\in K}\mu_3^k\left(\sum_{l\in L}\sum_{q\in Q_l}\sum_{j\in J}y_{qj}\sigma_{qk}-f_k\right)+ \\
& \sum_{n\in N}\mu_4^n\left(\sum_{q\in T_n}\sum_{j\in J}y_{qj}-a_n\right)+\sum_{n\in N}\mu_5^n\left(\sum_{q\in R_n}\sum_{j\in J}y_{qj}-d_n\right)
\end{aligned}
$$

Subject to:

$\sum_{p\in P_w}\sum_{i\in I_w}x_p^i$	$=$	1	$\forall w\in W$	(LR.1)
$\sum_{p\in P_w}\sum_{l\in L}x_p^i\delta_{pl}$	$\le$	θ	$\forall i\in I_w, w\in W$	(LR.2)
x_p^i	$=$	1 or 0	$\forall i\in I_w, p\in P_w, w\in W$	(LR.3)

$$\sum_{j \in J} y_{qj} \leq 1 \qquad \forall q \in Q_l, l \in L \qquad \text{(LR.4)}$$

$$y_{qj} = 1 \text{ or } 0 \qquad \forall q \in Q_l, l \in L, j \in J \qquad \text{(LR.5)}$$

$$f_k \in \{0,1,2,...,|J|\} \qquad \forall k \in K \qquad \text{(LR.6)}$$

$$a_n \in \{0,1,2,...,|A_n|\} \qquad \forall n \in N \qquad \text{(LR.7)}$$

$$d_n \in \{0,1,2,...,|D_n|\} \qquad \forall n \in N \qquad \text{(LR.8)}$$

$$\sum_{q \in Q_l} y_{qj}\sigma_{qk} \leq 1 \qquad \forall k \in K, j \in J, l \in L \qquad \text{(LR.9)}$$

Where μ_1, μ_2, μ_3, μ_4, μ_5 are the vectors $\{\mu_1^l\}$, $\{\mu_2^l\}$, $\{\mu_3^{kj}\}$, $\{\mu_4^k\}$, $\{\mu_5^n\}$, respectively, and μ_1, μ_2, μ_3, μ_4, μ_5 are the Lagrangian multipliers. μ_1, μ_2, μ_3, μ_4, $\mu_5 \geq 0$ To solve (LR), we keep on decomposing (LR) problem into the following independent, easily, and solvable optimization subproblems.

3.1.1 Subproblem 1 (related to decision variable x_p^i)

$$Z_{sub1}(\mu_1) = \min \sum_{l \in L} \sum_{w \in W} \sum_{p \in P_w} \sum_{i \in I_w} \mu_1^l x_p^i \lambda_w^i \delta_{pl}$$

Subject to:

$$\sum_{p \in P_w} \sum_{i \in I_w} x_p^i = 1 \qquad \forall w \in W \qquad \text{(sub1.1)}$$

$$\sum_{p \in P_w} \sum_{l \in L} x_p^i \delta_{pl} \leq \theta \qquad \forall i \in I_w, w \in W \qquad \text{(sub1.2)}$$

$$x_p^i = 1 \text{ or } 0 \qquad \forall i \in I_w, p \in P_w, w \in W \qquad \text{(sub1.3)}$$

Subproblem 1 can be further decomposed into |*W*| independent shortest path problems with arc weights μ_1^l, which are nonnegative value for each link. Since the hop count constraint, we can solve each shortest path easily by using Bellman-Ford algorithm [2]. Since the time complexity of Bellman-Ford algorithm is $O(|V| \times |E|)$, where $|E|$ represent the number of edges, the time complexity of this subproblem is $O\left(|W| \times |V| \times |E|\right)$.

3.1.2 Subproblem 2 (related to decision variable y_{qj})

$$
\begin{aligned}
Z_{sub2}(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5) = \min \sum_{l \in L} \mu_1^l \left(-\sum_{q \in Q_l} \sum_{j \in J} y_{qj} B \right) + \sum_{k \in K} \sum_{j \in J} \mu_2^{kj} \left(\sum_{l \in L} \sum_{q \in Q_l} y_{qj} \sigma_{qk} - 1 \right) + \\
\sum_{k \in K} \mu_3^k \left(\sum_{l \in L} \sum_{q \in Q_l} \sum_{j \in J} y_{qj} \sigma_{qk} \right) + \sum_{n \in N} \mu_4^n \left(\sum_{q \in T_n} \sum_{j \in J} y_{qj} \right) + \sum_{n \in N} \mu_5^n \left(\sum_{q \in R_n} \sum_{j \in J} y_{qj} \right) \\
= \min \sum_{l \in L} \sum_{q \in Q_l} \sum_{j \in J} \left[-\mu_1^l B + \sum_{k \in K} \left(\mu_2^{kj} + \mu_3^k \right) \sigma_{qk} \right] y_{qj} + \\
\sum_{n \in N} \sum_{q \in T_n} \sum_{j \in J} \mu_4^n y_{qj} + \sum_{n \in N} \sum_{q \in R_n} \sum_{j \in J} \mu_5^n y_{qj}
\end{aligned}
$$

Subject to:

$$\sum_{j \in J} y_{qj} \le 1 \qquad \forall q \in Q_l, l \in L \qquad \text{(sub2.1)}$$

$$y_{qj} = 1 \text{ or } 0 \qquad \forall q \in Q_l, l \in L, j \in J \qquad \text{(sub2.2)}$$

$$\sum_{q \in Q_l} y_{qj} \sigma_{qk} \le 1 \qquad \forall k \in K, j \in J, l \in L \qquad \text{(sub2.3)}$$

Subproblem 2 can be further decomposed into |*L*| problems for each logical link *l*. For each problem, we want to find *t* link-disjoint paths [14][15] from the source node, O, of logical link *l* to destination node, D, of logical link *l*, where μ_2^{kj} is the cost for using wavelength *j* on fiber link *k*, and μ_3^k is the cost for using the fiber link *k*. Hence, in the WDM Network, the arc cost is $\mu_2^{kj} + \mu_3^k$ (Figure 3-1). We construct number of $|J|$ WDM wavelength sub-network, each corresponding to a different wavelength *j* and applying WDM network topology. As illustrated in Figure 3-2. We split source and destination node into $|J|$ nodes in each sub-networks, respectively. For each logical link, since the wavelength continuity constraint, we can regard it as a k -link-disjoint shortest path problem with each link that can carry up to one wavelength bandwidth.

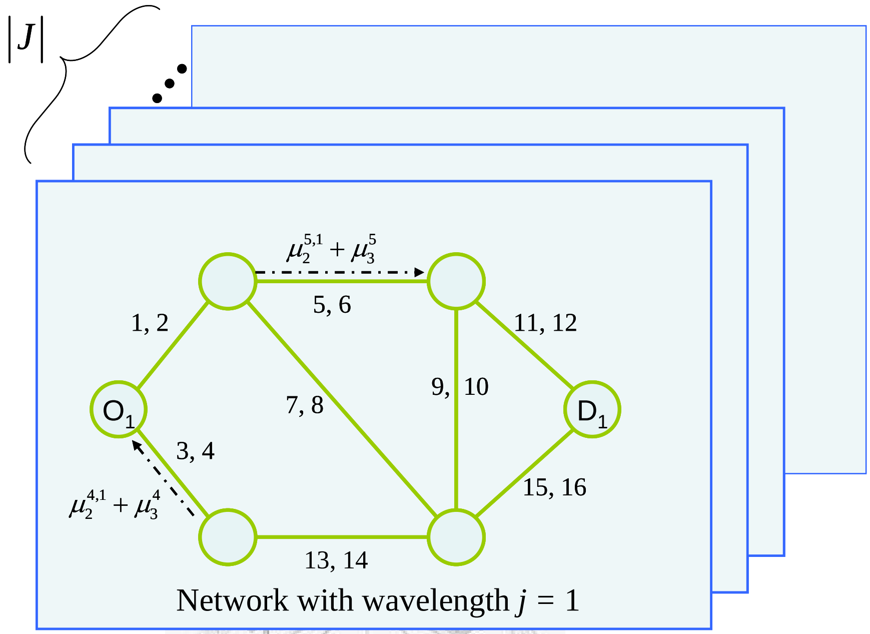

Figure 3-1 Cost for a WDM Link

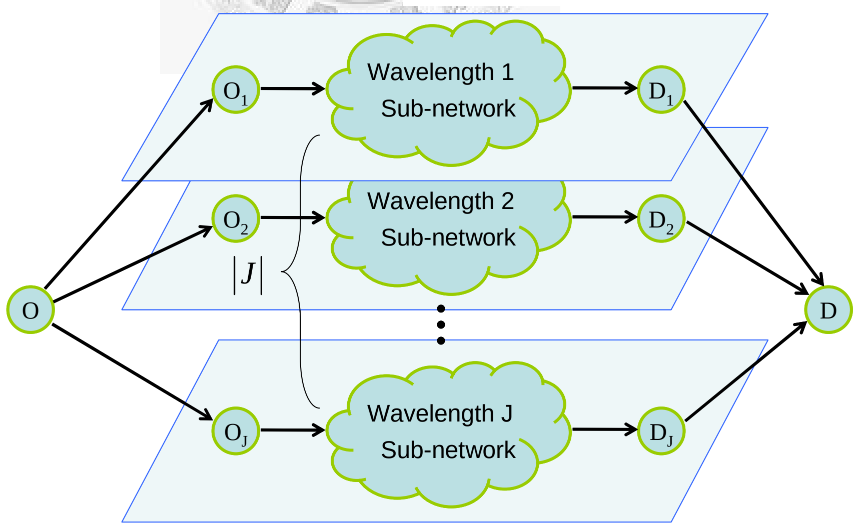

Figure 3-2 Decompose Network into Single Wavelength Sub-network

The subproblem, without generality, can be separated into $|L|$ problems, and the source node and the destination node are determined after a certain logic link is chosen. Thus, we modify the objective function as below to solve it more easily.

$$Z_{sub2}(\mu_1,\mu_2,\mu_3,\mu_4,\mu_5)$$
$$=\min\sum_{l\in L}\left[\sum_{q\in Q_l}\sum_{j\in J}\left(-\mu_1^l B+\sum_{k\in K}\left(\mu_2^{kj}+\mu_3^k\right)\sigma_{qk}\right)+\sum_{q\in T_{s(l)}}\sum_{j\in J}\mu_4^{s(l)}+\sum_{q\in R_{d(l)}}\sum_{j\in J}\mu_5^{d(l)}\right]y_{qj}$$
$$=\min\sum_{l\in L}\left[\sum_{q\in Q_l}\sum_{j\in J}\sum_{k\in K}\left(\mu_2^{kj}+\mu_3^k\right)\sigma_{qk}+\left(-\sum_{q\in Q_l}\sum_{j\in J}\mu_1^l B+\sum_{q\in T_{s(l)}}\sum_{j\in J}\mu_4^{s(l)}+\sum_{q\in R_{d(l)}}\sum_{j\in J}\mu_5^{d(l)}\right)\right]y_{qj}$$

The objective function above can be decomposed into two parts, first part is $\sum_{q\in Q_l}\sum_{j\in J}\sum_{k\in K}\left(\mu_2^{kj}+\mu_3^k\right)\sigma_{qk}y_{qj}$, which is a *t* link-disjoint shortest paths problem for each logical link *l*, and the second part is $\left(-\sum_{q\in Q_l}\sum_{j\in J}\mu_1^l B+\sum_{q\in T_{s(l)}}\sum_{j\in J}\mu_4^{s(l)}+\sum_{q\in R_{d(l)}}\sum_{j\in J}\mu_5^{d(l)}\right)y_{qj}$, which is constant revenue for each logical link *l* on condition that lightpath y_{qj} is set up. Since the marginal cost is positive when building up one additional lightpath, however, the marginal revenue is zero in the mean while. Therefore, we recognize that the combination of these two parts is a convex function (Figure 3-3).

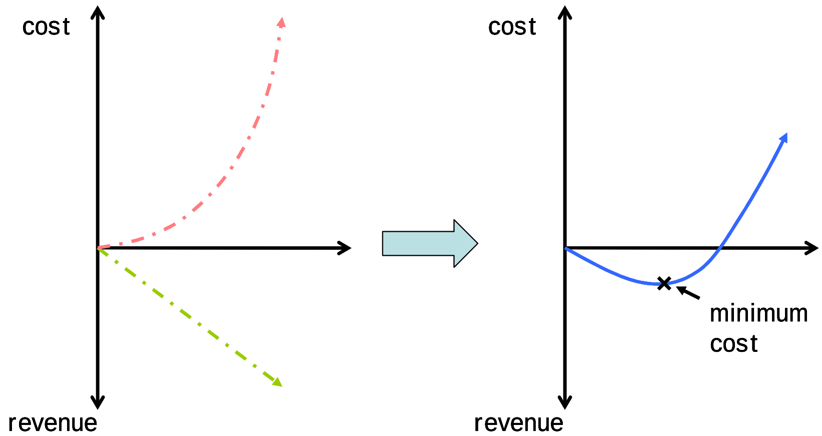

Figure 3-3 Convex Function Diagram

For each logical link *l*, we solve each problem by the following algorithm:

Initially: t = 0. REVENUE = $\left(-\sum_{q \in Q_l} \sum_{j \in J} \mu_1^l B + \sum_{q \in T_{s(l)}} \sum_{j \in J} \mu_4^{s(l)} + \sum_{q \in R_{d(l)}} \sum_{j \in J} \mu_5^{d(l)} \right)$

Step 1: If REVENUE is larger than or equal to zero, output the objective function value as zero and stop the algorithm. Otherwise, let t = t + 1 and CURRENT_OPTIMAL = INFINITY. Then, go to step 2.

Step 2: Solve the k-link-disjoint shortest paths problem from origin node, O, to destination node, D, which define the logical link l, in WDM mesh network for the first part of the objective function and the second part REVENUE * t. Go to step 3.

Step 3: If the objective function value computed from Step 2 is small than CURRENT_OPTIMAL, set this smaller value as CURRENT_OPTIMAL, and t = t + 1, then go to Step 2. Otherwise, output CURRENT_OPTIMAL as the optimal value of this objective function and stop the algorithm.

Since the time complexity of Suurballe's algorithm to find a shortest set of k link-disjoint paths from a given O-D pair is $O(k|E|\log_{1+|E|/|V|}|V|)$, for all logical link l, the method takes $O(|L| \times k|E|\log_{1+|E|/|V|}|V|)$ time. Hence, the time complexity of this subproblem is $O(|L| \times k|E|\log_{1+|E|/|V|}|V|)$, where $|E| = O(|J| \times |K|)$ and $|V| = O(|N| \times |J|)$. Among which, $|J|$ represents the number of wavelengths allocated in each fiber link and $|N|$ represents the number of OXCs in the WDM network.

3.1.3 Subproblem 3 (related to decision variable f_k)

$$Z_{sub3}(\mu_3) = \min \sum_{k \in K} \psi_k(f_k) - \sum_{k \in K} \mu_3^k f_k$$

Subject to:

$$f_k \quad \in \quad \{0,1,2,...,|J|\} \qquad \forall k \in K \qquad \text{(sub3.1)}$$

The subproblem can be decomposed into $|K|$ independent problems. For each fiber link *k*, there are only two possibilities for decision variable f_k:

Case 1: If $\psi_k(f_k) - \mu_3^k < 0$, then $f_k = |J|$.

Case 2: If $\psi_k(f_k) - \mu_3^k \geq 0$, then $f_k = 0$.

3.1.4 Subproblem 4 (related to decision variable a_n)

$$Z_{sub4}(\mu_4) = \min \sum_{n \in N} \psi_{nt}(a_n) - \sum_{n \in N} \mu_4^n a_n$$

Subject to:

$$a_n \quad \in \quad \{0,1,2,...,|A_n|\} \qquad \forall n \in N \qquad \text{(sub4.1)}$$

The subproblem can be decomposed into $|n|$ independent problems. For each node *n*, there are only two possibilities for decision variable a_n:

Case 1: If $\psi_{nt}(a_n) - \mu_4^n < 0$, then $a_n = |A_n|$.

Case 2: If $\psi_{nt}(a_n) - \mu_4^n \geq 0$, then $a_n = 0$.

3.1.5 Subproblem 5 (related to decision variable d_n)

$$Z_{sub5}(\mu_5) = \min \sum_{n \in N} \psi_{nr}(d_n) - \sum_{n \in N} \mu_5^n d_n$$

Subject to:

$$d_n \quad \in \quad \{0,1,2,...,|D_n|\} \qquad \forall n \in N \qquad \text{(sub5.1)}$$

The subproblem can be decomposed into $|n|$ independent problems. For each node *n*, there are only two possibilities for decision variable d_n:

Case 1: If $\psi_{nr}(d_n) - \mu_5^n < 0$, then $d_n = |D_n|$.

Case 2: If $\psi_{nr}(d_n) - \mu_5^n \geq 0$, then $d_n = 0$.

3.2 The Dual Problem and the Subgradient Method

According to the weak Lagrangian duality theorem [4], for any set of multipliers $\mu_{1,}\ \mu_{2,}\ \mu_{3,}\ \mu_{4,}$ and $\mu_{5,} \geq 0$, $Z_D(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5)$ is a lower bound on Z_{IP}. We construct the following dual problem to calculate the tightest lower bound.

Dual Problem (D)

$$Z_D = \max Z_D(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5)$$

Subject to:

$$\mu_1, \mu_2, \mu_3, \mu_4, \mu_5 \geq 0$$

The most popular method for solving the dual problem (D) is the subgradient method. We adopted as our solution approach to the dual problem. Let the vector *S* be a subgradient of $Z_D(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5)$. In iteration *k* of the subgradient optimization procedure, the multiplier vector $m^k = (\mu_1^k, \mu_2^k,$

$\mu_3^k, \mu_4^k, \mu_5^k)$ is updated by $m^{k+1} = m^k + \alpha^k S^k$. The step size α^k is determined by $\alpha^k = \delta \frac{Z_{IP}^h - Z_D(m^k)}{\left\| S^k \right\|^2}$, where Z_{IP}^h is the primal objective function value, an upper bound on optimal primal objective function value, and δ is a constant between 0 and 2.

Chapter 4 Getting Primal Feasible Solutions

4.1 Lagrangian Relaxation Results

By using Lagrangian relaxation and the subgradient method, we can get a theoretical lower bound of the primal problem. In addition, from the solutions of the Lagrangian relaxation problem and multipliers per iteration, it provides some hints to help us obtain primal feasible solution [10].

If the calculated decision variables happen to satisfy the relaxed constraints in the primal problem, a primal feasible solution is found. Otherwise, we use the infeasible primal solution as a good start point to get a primal feasible solution.

4.2 Getting Primal Heuristics

Since the complexity of the primal problem, we divide overall problem into three subproblems. The first one is to keep the add/drop constraint for each node. The second is to be construction of logical layer topology, which modifies the O-D pair traffic routing according to the result of dual problem in a complete graph. After the determination of routing paths, we then deal with WDM network lightpath routing and wavelength assignment subproblem as the third.

4.2.1 Heuristic for Keeping Add/Drop Port Constraint

Subproblem

In the subproblem, we must check whether the add/drop port constraint is followed in each OXC node when the traffic of each O-D pair routes in the logical network. To solve this subproblem, the result of Subproblem 1, $\{\sum_{i\in I_w} x_p^i = x_p\}$, is a good starting point to get the feasible solution for traffic routing. The algorithm is described below:

Step 1: Based on $\{x_p\}$, calculate aggregate flow on each logical link in the Logical Network.

Step 2: Find out the set of nodes at which the drop port constraint violates, denoted $\{N_d\}$; denoting $\{N_a\}$ as the set of nodes with add port constraint violation in the similar way. If N_d and N_a are both empty, stop the algorithm, else if N_d is not empty, go to Step 3, else if N_a is not empty go to Step 7.

Step 3: Consider the drop port constraint first. Remove one $n \in N_d$ with most serious violation; identify the set of logical link which are in-degree of *n*, denoted $\{L_n\}$.

Step 4: Remove one $l \in L_n$ with heaviest demand on it; identify the O-D pair set that routed traffic on *l* except the O-D pairs terminate at a certain node $n_x \in N_d$ or originate from a certain node $n_y \in N_a$, denoted by $\{O_l\}$.

Step 5: Select $o \in O_l$ with heaviest demand, take the traffic away, and re-route it without passing through those logical links on the condition that if it carries the traffic request by *o* it will induce violation of add/drop constraint.

Step 6: Repeat Step 5 until one of the two cases happens. Case 1: node *n* keeps the drop constraint, go to Step 2. Case 2: The set O_l is empty, go to Step 4.

Step 7: In the stage, we will consider the add port constraint violation.

Fortunately, the method is similar as consider the drop port constraint violation from Step 3 to Step 6. Hence, we do not give unnecessary detail.

4.2.2 Heuristic for Constructing Logical Layer Topology Subproblem

In the subproblem, we must decide how many numbers of lightpaths need to be built up in each logical link, and the routing logical-path for each O-D pair. Since the cost is dominated at the number of leased add/drop ports. And the number of transceivers employed in the network only depends on the number of lightpaths set up. Hence, the less lightpaths needed, the less cost we pay. Though we can get a feasible logical layer topology for routing decisions in 4.2.1, it does not try best to groom the traffic into the fewer lightpaths as possible. The logical layer topology may be loose and the cost is over-estimated from the optimal solution. To refine the quality of primal feasible solution, we then apply the below algorithm to remove dispensable logical links to make traffic grooming tighter:

From 4.2.1 we can get a set of logical link *L*, denote logical layer topology formed by *L* as *G*.

Step 1: Select one $l \in L$ with slightest demand, identify the O-D pair set that has routed traffic on *l*, denoted by O_l.

Step 2: Select $o \in O_l$ with heaviest traffic request, take the traffic away, and re-route it without passing through link *l* and not to violate the add/drop constraint. If re-route fails, then recovery the route for this O-D pair and the traffic on each link that *o* travels formerly, and then stop the algorithm.

Otherwise, go to Step 3.

Step 3: Repeat Step 2 until O_l become empty.

Step 4: Remove *l* from *G*, and update topology $G = G - l$. Go to Step 1.

After applying this algorithm, we can get a new logical layer topology with much lower leased cost than before.

4.2.3 Heuristic for Routing and Wavelength Assignment Subproblem

In the formulation, we assume that lambdas are always available, so admission control does not consider in the thesis. Hence, after constructing logical layer topology from 4.2.2, we apply the following algorithm to deal with WDM network lightpath routing and wavelength assignment subproblem:

Step 1: Calculate the total lightpaths needed for each logical link *l* based on the total traffic on it and TDM capacity of each wavelength.

Step 2: Select the logical link *l* with most number of lightpaths it needs, assume it needs number of *k*, using Suurballe's Algorithm [14][15] to find k link-disjoint shortest paths in the WDM network with the arc weight, $\mu_2^{kj} + \mu_3^k$, which is calculated in Lagrangian Relaxation Subproblem 3. And then, let the used arc link weight infinite.

Step 3: If all the logical links has been selected, then stop the algorithm; else go to Step 2.

Chapter 5　Computational Experiments

For the purpose to show the difference of solution quality between the algorithms proposed in this thesis from the Lagrangian relaxation method and other primal heuristics, we have aspiration for development of another simple algorithm to compare with our heuristics. With the comparison of the result, we can not only examine the quality of our primal heuristics, but also get some implications from the Lagrangian multipliers to find a feasible solution.

5.1 Simple Algorithm (SA)

By no means can we properly adjust the link weight without implications of Lagrangian multipliers. Because of this, the weight of each link is not modified in the processes of simple algorithm. In our problem, there are two types of link, one is logical link in the complete graph, and the other is physical link in WDM network. In the complete graph, the dominant cost is the charges for leasing add/drop ports. By the way, when a logical link is used we may lease one add port at originating node and one drop port at terminating node. As a whole, using the cost of the originating node plus the cost of terminating node as the weight of the logical link is a good idea. And without loss of generality, we use the fiber cost as physical link weight. The proposed simple algorithm is presented as follows:

Step 1: For each O-D pair *w*, apply Bellman-Ford algorithm to calculate the shortest path in the logical network.

Step2: Use the same algorithms described in section 4.2 to determine that keeping add/port constraint, reconstructing the logical layer topology and the routing and wavelength assignment, respectively.

After applying the simple algorithm above, we will find a feasible solution of the objective function of our problem formulation described in section 2.3.

5.2 Lagrangian Relaxation Based Algorithm (LR)

This algorithm is based on the mathematical formulation described in Chapter 2 . The relaxation problem is then solved optimally as described in Chapter 3 to get a lower bound for the primal problem. After then, the algorithms described in Chapter 4 are embraced for getting a primal feasible solution. And we use a subgradient method to update the Lagrangian multipliers. Summarize, the Lagrangian relaxation based algorithm is presented below:

Step 1 (Initialization) :

1) Read configuration file to construct logical layer network topology, WDM network and O-D pair traffic demand.
2) Initialize constant parameters, multipliers, improvement counter to be 40, iteration counter *i* to be 1.
3) Initialize upper bound value (UB) as each O-D pair traffic demand uses one logical link in complete graph and uses one lightpath in WDM network.
4) Initialize lower bound value (LB) to be zero.

Step 2 (Termination Criteria):

If the error rate between upper bound and lower bound is adequate small or iteration counter i reaches desired iterations, stop the algorithm. Otherwise, go to next step.

Step 3 (Solving Lagrangian Dual Problem):

With the given Lagrangian multiplier, optimally solve subproblems described in Chapter 3 for receipt of the value Z_d .

Step 4 (Getting Primal Feasible Solution):

Apply the heuristics described in Chapter 4 for receipt of the value Z_{IP}

Step 5 (Update UB, LB, and Lagrangian Multipliers):

1) If Z_d > LB, then LB = Z_d

2) If Z_{IP} < UB, then UB = Z_{IP}, then reset improvement counter as 40. Otherwise, decrease 1 at improvement counter.

3) Calculate step size and update Lagrangian multipliers by using subgradient method described in section 3.3.

4) Increase 1 at iteration counter i, and go to Step 2.

5.3 Parameters and Cases of the Experiment

Table 5-1 Command Parameters for All Case

Number of Iterations	1000
Improvement Counter	40
Begin to Tune Iteration	70

Initial Upper Bound	Cost of non Traffic Grooming
Initial Scalar of Step Size	2
Hop Distance	3
Cost of leasing add/drop port	50 ~ 100
Cost of leasing wavelength per Physical Link	5 ~ 10

The network topology used for our numerical experiments are Mesh-1 network (Figure 5-1), GTE network (Figure 5-2), NSF network (Figure 5-3) and Mesh-2 network (Figure 5-4).

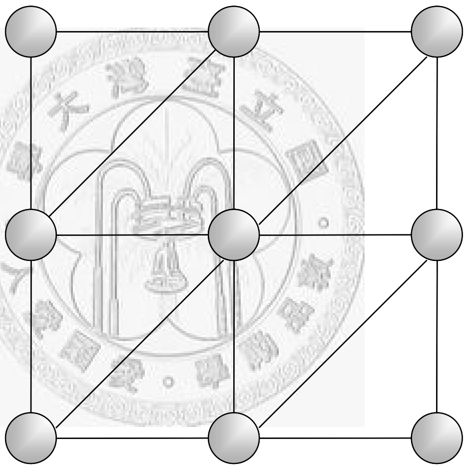

Figure 5-1   Mesh-1 Network: 9 Nodes, 32 Links

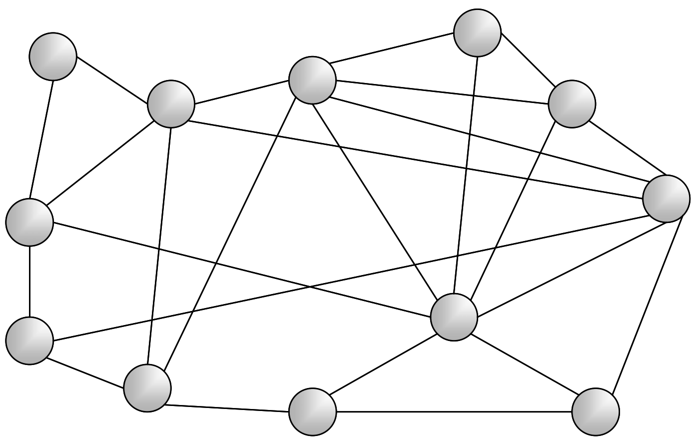

Figure 5-2   GTE Network: 12 Nodes, 50 Links

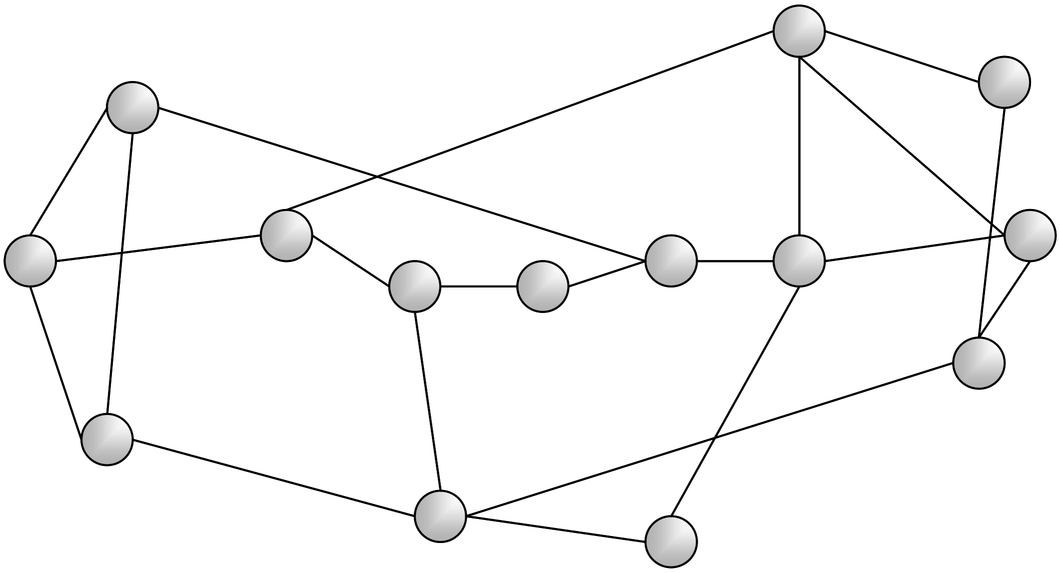

Figure 5-3   NSF Network: 14 Nodes, 42 Links

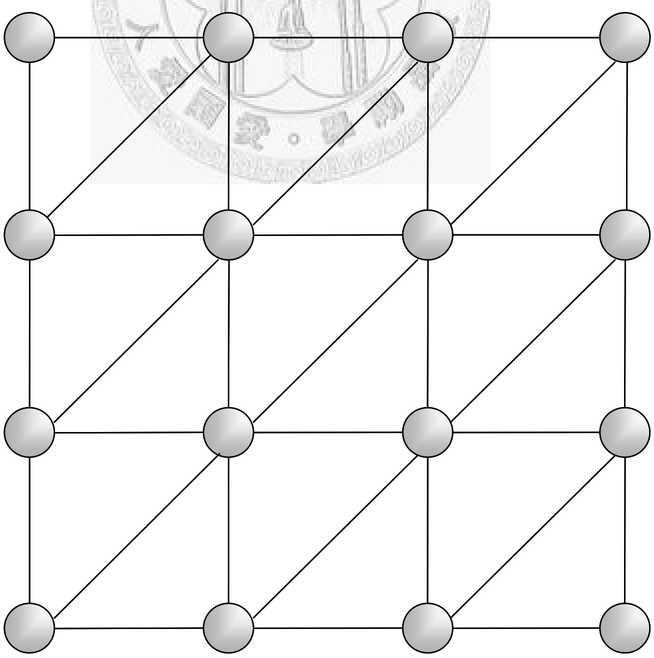

Figure 5-4   Mesh-2 Network: 16 Nodes, 66 Links

Table 5-2 Parameters Setting in All Test Cases

Case	Demand	Time Slot (BW)	Wavelength	Add/Drop Port	Seed	Network Model
1	0 ~ 4	8, 10, 12	4	9	100/200	Mesh-1
2	0 ~ 4	8, 10, 12	5	12	100/200	GTE
3	0 ~ 4	8, 10, 12	9	15	100/200	NSF
4	0 ~ 4	8, 10, 12	8	20	100/200	Mesh-2
5	0~3 0~6 0~9	13	7	14	100/200	GTE

5.4 Experiment Results

Table 5-3 Computation Result of Case 1 (Mesh-1 Network)

Seed	BW	SA	LR	LB	Gap (%)	Imp (%)	SA Li	LR Li
100	8	3317.2	3031.4	1944.2	55.92	8.62	37	34
	10	2908.1	2541.1	1719.3	47.79	12.62	33	28
	12	2702.3	2269.1	1537.9	47.55	16.03	30	25
200	8	3826.7	3526.3	2417.3	45.88	7.85	40	38
	10	3291.5	2947.9	1984.3	48.56	10.44	35	32
	12	3087.1	2605.2	1814	43.62	15.61	32	28

Table 5-4 Computation Result of Case 2 (GTE Network)

Seed	BW	SA	LR	LB	Gap (%)	Imp (%)	SA Li	LR Li
100	8	6413.1	5826.3	3599	61.89	9.15	69	63
	10	5782.6	4903.1	3048.1	60.86	15.21	62	53
	12	5168.1	4212.3	2614.4	61.12	18.49	56	47
200	8	6763.4	6295.2	3876.7	62.39	6.92	72	65
	10	5826.2	5145.9	3249.5	58.36	11.68	63	56
	12	5294.8	4496.9	2736.7	64.32	15.07	58	47

Table 5-5 Computation Result of Case 3 (NSF Network)

Seed	BW	SA	LR	LB	Gap (%)	Imp (%)	SA Li	LR Li
100	8	8514.2	7970.4	4907.6	62.41	6.39	94	89
	10	7668.7	6842.1	4145	65.07	10.78	82	76
	12	7013.6	6026.3	3574.9	68.57	14.08	75	69
200	8	8376.3	7908.6	4829.5	63.76	5.58	91	87
	10	7392.4	6548.8	3727.5	75.69	11.41	81	73
	12	6864.8	5894.8	3303.1	78.46	14.13	74	66

Table 5-6 Computation Result of Case 4 (Mesh-1 Network)

Seed	BW	SA	LR	LB	Gap (%)	Imp (%)	SA Li	LR Li
100	8	11709	11217	7130.2	57.32	4.20	120	114
	10	11046	9705.1	6068.7	59.92	12.14	114	100
	12	10119	8289.1	5408.3	53.27	18.08	103	86
200	8	12743	12013	7122.7	68.66	5.73	125	116
	10	11463	10041	5903.1	70.10	12.41	111	97
	12	10611	8646.1	5260.7	64.35	18.52	103	87

Table 5-7 Computation Result of Case 5 (GTE Network)

Seed	Traffic	SA	LR	LB	Gap (%)	Imp (%)	SA Li	LR Li
100	0 ~ 3	3717.5	3182.2	2049.1	55.30	14.40	42	36
	0 ~ 6	6468.9	5786.2	3567.2	62.21	10.55	68	63
	0 ~ 9	8338.2	7740.2	4703.8	64.55	7.17	88	83
200	0 ~ 3	3782.3	3373.4	1978.1	70.54	10.81	40	37
	0 ~ 6	6250.1	5613.8	3262.7	72.06	10.18	67	59
	0 ~ 9	8973.1	8266.9	5217.5	58.45	7.87	94	87

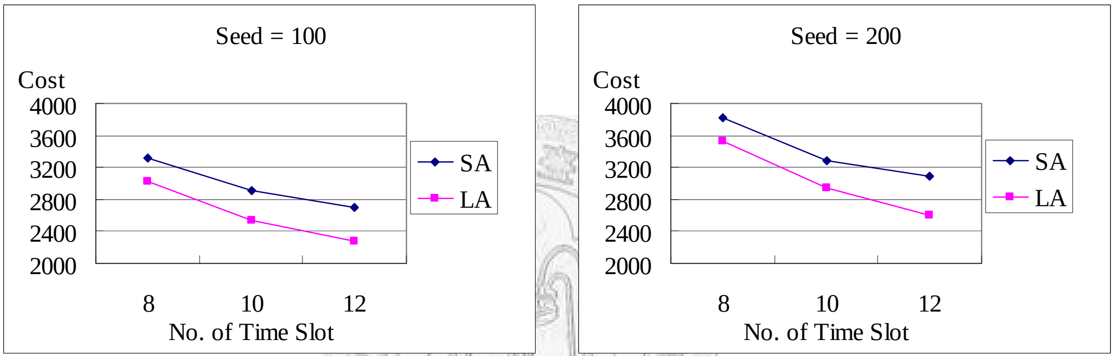

Figure 5-5 Comparison of Leasing Cost in Case 1

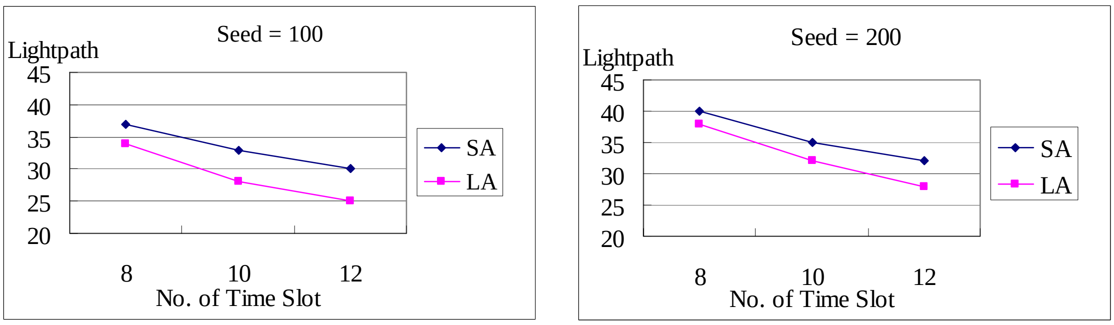

Figure 5-6 Comparison of Number of Leasing Lightpaths in Case 1

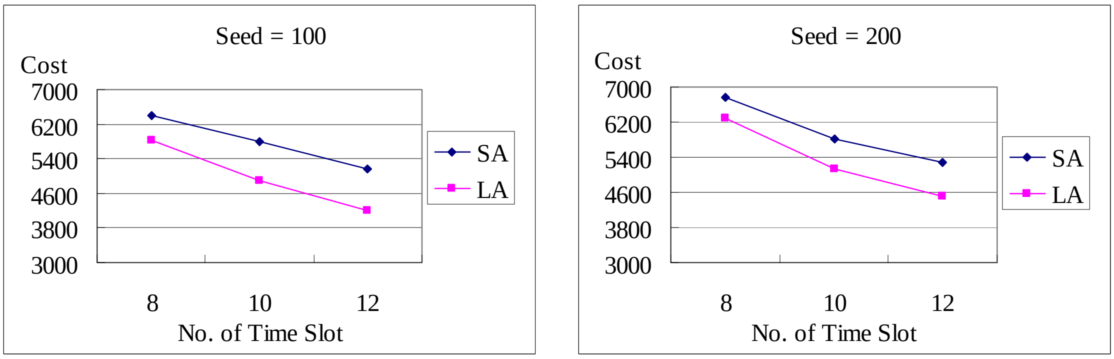

Figure 5-7　Comparison of Leasing Cost in Case 2

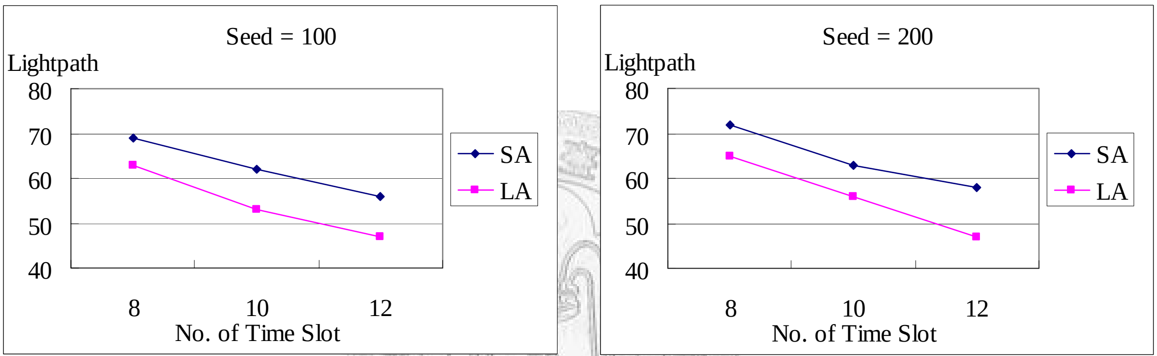

Figure 5-8　Comparison of Number of Leasing Lightpaths in Case 2

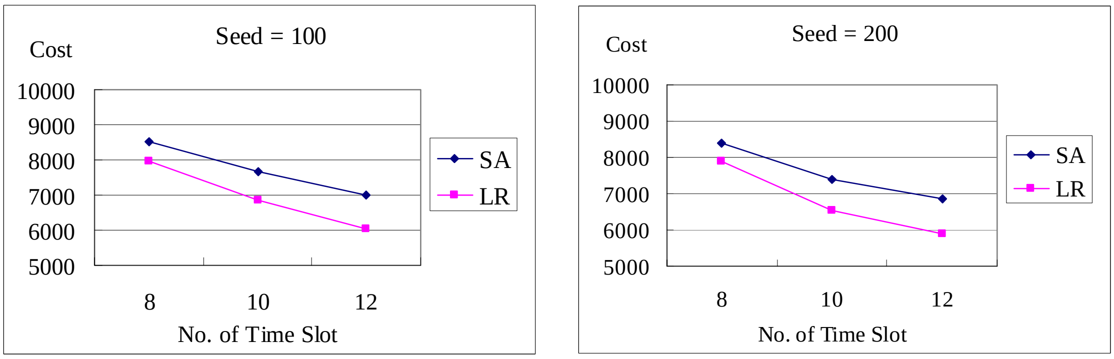

Figure 5-9　Comparison of Leasing Cost in Case 3

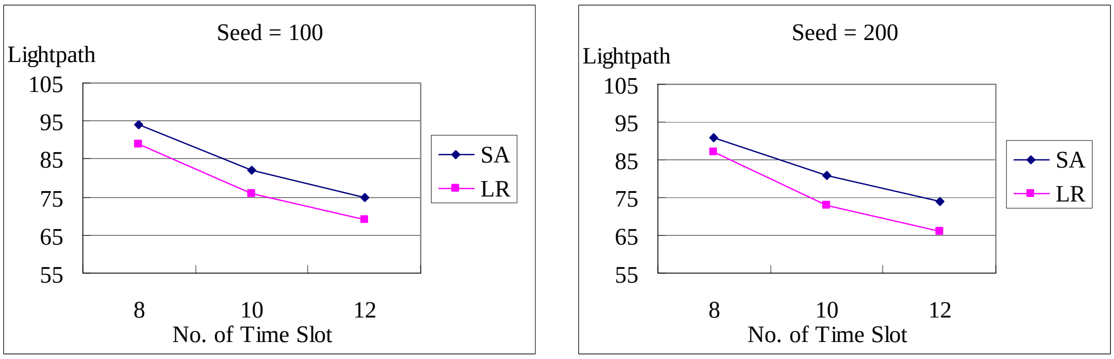

Figure 5-10　Comparison of Number of Leasing Lightpaths in Case 3

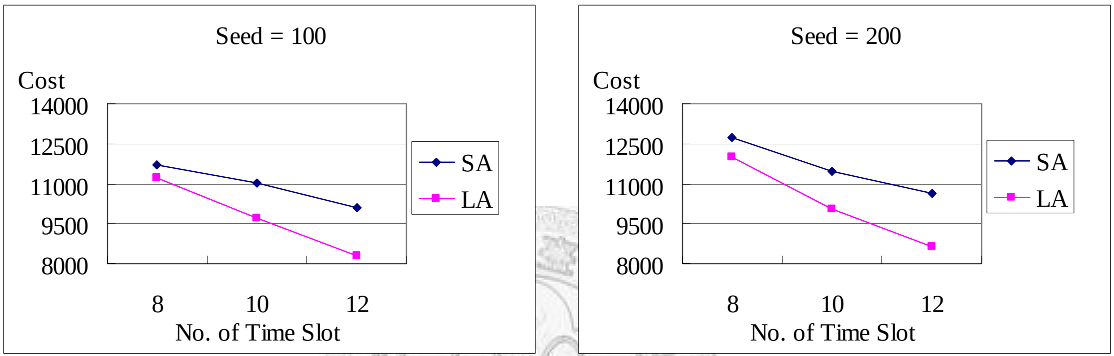

Figure 5-11　Comparison of Leasing Cost in Case 4

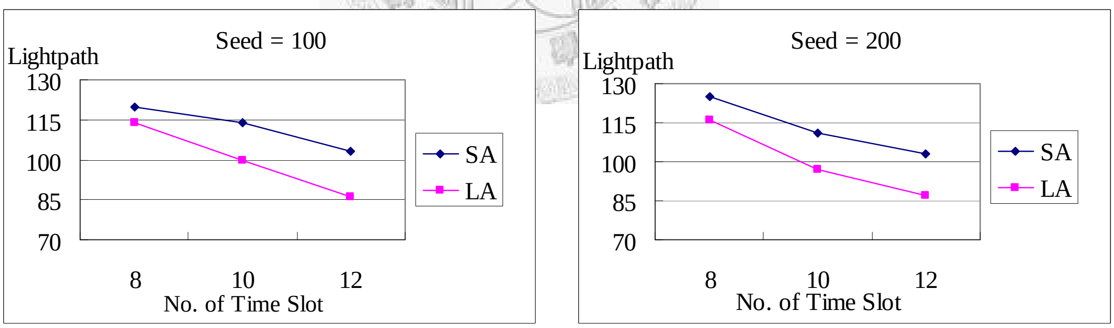

Figure 5-12　Comparison of Number of Leasing Lightpaths in Case 4

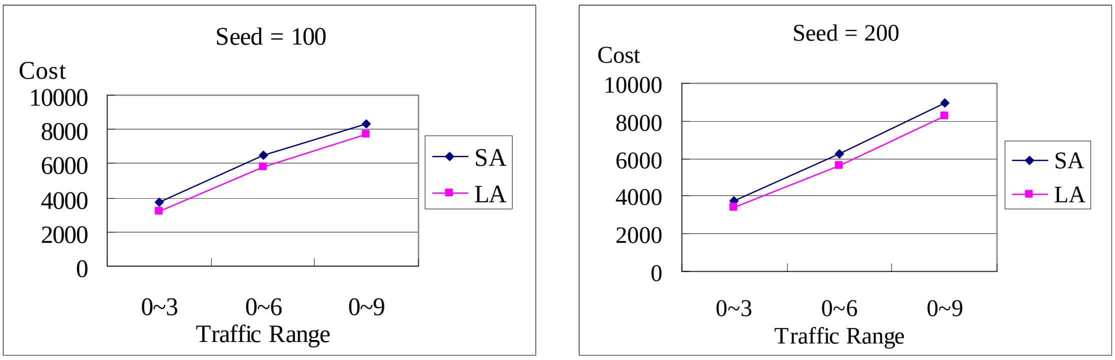

Figure 5-13 Comparison of Leasing Cost in Case 5

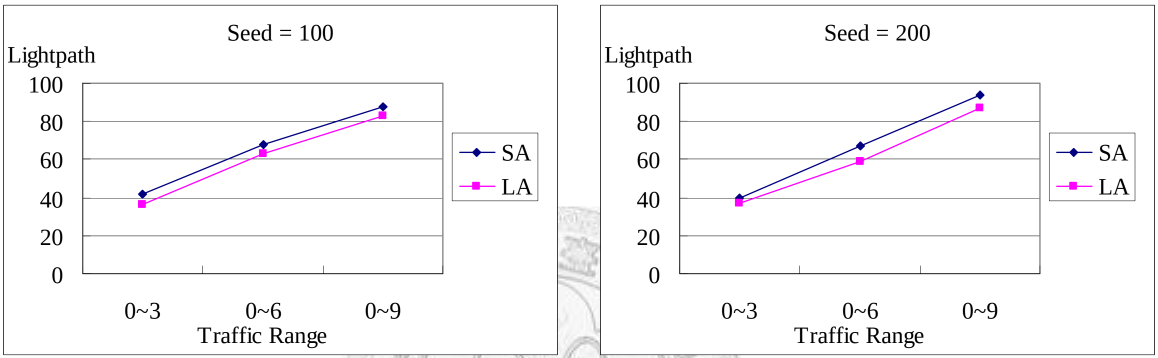

Figure 5-14 Comparison of Number of Leasing Lightpaths in Case 5

5.5 Computation Time

Table 5-8 Computation time of different cases running 1000 iterations

Computation Time (s)							
Seed	BW	Case 1	Case 2	Case 3	Case 4	Traffic	Case 5
100	8	54	248	747	1066	0 ~ 3	265
	10	53	235	737	1000	0 ~ 6	300
	12	52	232	721	981	0 ~ 9	335
200	8	52	237	771	1026	0 ~ 3	274
	10	51	237	741	996	0 ~ 6	290
	12	49	232	720	953	0 ~ 9	319

From Table 5-8, the computation time increase while number of nodes in different network topologies grows. There are two reasons for this. First, the total traffic in the network augments proportional to the number of O-D pairs. Second, the number of wavelengths allocated in each fiber should increase to fit the traffic routing and wavelength assignment in the WDM network while the total traffic grows.

In addition, the running time per iteration of the Lagrangian relaxation based algorithm is slightly higher than simple algorithm.

5.6 Result Discussion

The results of LR are all better than SA. There are two reasons that LR works better than SA. First, SA algorithm makes traffic routing decision only based on the hop count and leasing cost for each add/drop port, whereas LR makes use of the related multipliers, including the influence not only the hop count and leasing cost for each add/drop port but also the potential cost routing and wavelength assignment on each physical link in the selected topology.

Second, LR is iteration-based and is guaranteed to improve the solution quality iteration by iteration. Moreover, the result per iteration can also be used as a good hint to improve the lower bound of the problem, which leads to good feasible solutions.

Chapter 6 Summary and Future Work

6.1 Summary

This study is devoted to design traffic routing, lightpath routing and wavelength assignment in optical WDM mesh networks in order to minimum the total leasing cost for network service provider upon the underlying network topology. It is assume that OXCs are equipped with grooming capacity but no wavelength converter.

One of the achievements in this thesis is that we present a precise mathematical formulation to describe the overall problems about traffic routing, lightpath routing and wavelength assignment in such a WDM mesh network. And the other is about performance, the proposed Lagrangian relaxation and subgradient based algorithm has more significant solutions to the problem as we can see from the results of the computational experiments.

Different network topologies are tested in experiments, including NSF network, GTE network and Mesh network. And different types of parameters setting, including different number of wavelengths available in optical fiber, different number of time slots available in one single wavelength, different number of add/drop ports and different traffic demands have been tested to make this thesis more generic. Due to the complexity of such a problem, we suggest network-related operators apply the proposed Lagrangian relaxation and subgradient based algorithm to deal with associated network design problems because it not only provide us some hints to improve our heuristics but can get a acceptable solution in limited time.

6.2 Future Work

In this paper, only the hop count limitation is considered about Quality of Service (QoS). However, due to the rapidly growing traffic demands in the networks, the failure of a network element can cause the failure of several lightpaths, leading to large date and revenue loss. Survivability management schemes are essential to survive such failures. How to efficiently groom low-speed connections with satisfying their protection requirements is one of the main issues of future work.

Besides, multicast applications such as video on demand and interactive games are becoming more and more popular. It is reasonable to apply optical multicast in WDM network for such multipoint applications. Base on the algorithms developed in this thesis, it is feasible to extend our work into the multicast environment.

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