國 立 交 通 大 學

資訊科學與工程研究所

碩 士 論 文

階層式交換器光纖網路上通道設置與保護之理論分析

Theoretical analysis of tunnel allocation in survivable MG-OXC networks

研 究 生：郭修嘉

指導教授：陳 健 教授

中 華 民 國 九 十 五 年 七 月

階層式交換器光纖網路上通道設置與保護之理論分析

Theoretical analysis of tunnel allocation in survivable MG-OXC networks

研 究 生：郭修嘉　　Student：Xiu-Jia Kuo

指導教授：陳　健　　Advisor：Chien Chen

國 立 交 通 大 學

資 訊 科 學 與 工 程 研 究 所

碩 士 論 文

A Thesis

Submitted to Institute of Computer Science and Engineering

College of Computer Science

National Chiao Tung University

in partial Fulfillment of the Requirements

for the Degree of

Master

in

Computer Science

July 2005

Hsinchu, Taiwan, Republic of China

中華民國九十五年七月

階層式交換器光纖網路上通道設置與保護之理論分析

研究生 : 郭修嘉　　　　　　　　　　指導教授: 陳　健

國 立 交 通 大 學 資 訊 科 學 與 工 程 系

中文摘要

在多單位交換器光纖網路中，數個綁成一束的連續波長形成一個通道(tunnel)並且像一個單獨波長一樣一起做交換。通道路徑上的交換器尺寸可因此而變小並降低成本。我們提供了一個 0/1 整數線性規畫(Integer Linear Programming)來解決多單位交換器光纖網路中長度固定的通道設置問題。先前的輔助圖模型被擴充成階層式的輔助圖模型來配合此整數線性規畫(ILP)。我們另外比較了其他種演算法，包括 CBSTA，WTA 和 PCWTA。在數種光纖組合和網路拓樸下，模擬結果都顯示出 PCWTA 和 WTA 優於 CBSTA，且他們都相當接近我們用整數線性規畫所求出的最佳解。接著在通道長度固定的假定下，我們分析各種通道長度對網路阻塞率的影響。這個假定出現在之前其他作者的論文中，但是該作者並沒有很仔細的解釋在該假定下，何種通道長度為最佳與其動機。一個利用 Erlang Loss Formula 來設計出的阻塞率模型在此被提出，並用來評估各種通道長度的優劣。在數個不同的網路拓樸下，此模型分析出的結果十分接近我們另外做的模擬結果，我們因而發現最佳的通道長度與網路拓樸是有相關的。最佳的通道長度應該要接近網路中節點之間的平均距離。

我們接著探討單一線路故障時的保護機制。一個名叫通道式分段保護的機制(TSP)已被發表來回復因線路故障所中斷的通訊。在通道已被設置好之後，我們

再提出一新的整數線性規畫來解決靜態的路由與波長分配問題,並且將備份的頻寬分享機制考慮進來。模擬結果顯示出 TSP 能勝過另一種更直覺的保護機制(TPP)。

關鍵字:多單位光學交換器、通道、容量平衡通道配置法、權重通道配置法、通道式分段保護機制、整數線性規畫。

Theoretical analysis of tunnel allocation in survivable MG-OXC networks

Student: Xiu-Jia Kuo **Advisor: Dr. Chien Chen**

Institute of Computer Science and Engineering
National Chiao Tung University

Abstract

Multi-granularity Optical Cross-Connect (MG-OXC) has been proposed to provide a cost-efficient way to support the growing demand for bandwidth. In the MG-OXC networks, consecutive wavelengths are bundled to form a tunnel and then switched as a single unit. Network resources at the intermediate nodes on the route of a tunnel, including switching fabrics and multiplexers, can thus be reduced. We suggest a 0/1 Integer Linear Programming (ILP) formulation for RWA with tunnel allocation in MG-OXC networks under tunnel length constraint. The previous auxiliary graph model is extended to a layered auxiliary graph model to facilitate the formulation. We compare the performance of different heuristics, including CB-STA, WTA and PCWTA, to the ILP solution. The simulation results show that PC-WTA and WTA outperforms CB-STA in all switching type combinations and network topologies, and they are very close to the optimal value calculated from our ILP formulation.

We further analyze the impact of tunnel length on blocking rate based on the hypothesis of fixed tunnel length constraint. This hypothesis occurred in previous

work, but the authors didn't explain its motivation clearly. A blocking probability model used Erlang loss formula is provided to estimate the performance of tunnel allocation with different tunnel length constraint. Based on the analytical results, which have proved to be very close to the simulation results, obtained from various kinds of networks, we find that the best performance on the length of a tunnel is related to the network topology. To put it plainly, the most suitable length of a tunnel should be the smallest integer greater than the average hop distance or the smallest integer greater than the average hop distance plus 1.

Then we aim to provide an efficient fault-recovery protection scheme for the lightpaths. A segment-based protection scheme, called Tunnel Based Segment Protection (TSP) is proposed to recover the communications interrupted by a fiber cut in previous work. After tunnel has been allocated, we suggest another ILP formulation to solve the static RWA problem with concept of sharing backup capacity. Simulation results show that the network performance is improved comparing to adapt a straightforward path protection scheme (TPP) for the MG-OXC networks.

Keywords: Multi-granularity Optical Cross-Connect, tunnel, Capacity-Balanced Static Tunnel Allocation, Weighted Tunnel Allocation, Tunnel-based Segment Protection, Integer Linear Programming.

誌謝

本篇論文的完成，我要感謝這兩年來給予我協助與勉勵的人。首先要感謝我的指導教授 陳健博士，讓我在遇到挫折時得以堅持下去，遇到困難時得以順利解決問題，在研究上處處碰壁時指引明路讓我得以順利完成本篇論文，在此表達最誠摯的感謝。同時也感謝我的論文口試委員，交大的曾煜棋教授、陳榮傑教授及央大的許健平教授，他們提出了許多的寶貴意見，讓我受益良多。

感謝長期以來一直照顧我的學長陳盈羽，由於他在論文上的協助，使我能突破瓶頸，研究也更為完善。另外我也要感謝實驗室的同學們，高游宸、周家聖、江長傑、陳健凱以及莊順宇等人，感謝他們陪我度過這兩年辛苦的研究生活，在我需要協助時總是不吝伸出援手，陪我度過最煩躁與不順遂的日子。

最後，我要感謝家人對我的關懷及支持，他們含辛茹苦的栽培，使我得以無後顧之憂的專心於研究所課業與研究，我要向他們致上最高的感謝。

Table of Content

List of Figures

Chapter 1: Introduction

Wavelength-division-multiplexing (WDM) networks have emerged as a method of providing Terabits-per-second capacity for ever-increasing bandwidth demands. Such a network is composed of optical cross-connects (OXCs) interconnected by fiber links, with each fiber supporting tens to hundreds of wavelength channels. End users in the network communicate with each other via one or several all-optical channels, i.e., lightpaths, with transmission rate ranging from one to tens of Gigabits per second.

Although increase in number of wavelength channels and fibers between node pairs may increase the available capacity, this may cause a scalability problem in maintenance and manufacturing of the optical cross-connects (OXCs). An effective way of handling this problem is to bundle a group of consecutive wavelength channels together and switch them as a single unit on a specific route to reduce the required resources of intermediate cross-connects along the route. The tunnel-like passage created by the bundled wavelength channels is defined as a waveband/fiber tunnel. Wavelengths in a tunnel must be switched together except at the two ends of the tunnel. Nodes that support such multigranularity switching, e.g. wavelength, waveband and fiber-switching, are termed hierarchical cross-connects or multigranularity optical cross-connects (MG-OXCs). This thesis examines the tunnel allocation and protection problems related to the networks that using the node architecture, MG-OXC.

1.1 Multi-Granularity Optical cross-Connects (MG-OXC)

The network is based on the node architecture [1] shown in Fig. 1. A MG-OXC mainly comprises fiber-, waveband-, and wavelength-switching boxes and waveband

and wavelength multiplexer/de-multiplexers. The fiber- and waveband-switching boxes on the left-hand side serve as selectors on the input fibers and wavebands while the fiber- and waveband-switching boxes on the right-hand side serve as OXCs that switch fibers and wavebands. In MG-OXC networks, a tunnel is defined as a group of consecutive wavelength channels that are bundled and switched together as a single unit, which could be either a fiber or waveband tunnel depending on the size of the grouped wavelengths. All of the channels in a waveband or fiber tunnel must be switched together. A tunnel is said to be *allocated* if link capacity along the route of the tunnel is dedicated to that tunnel. For an allocated tunnel to be used by lightpaths, a sufficient number of wavelength-switching ports at the ingress and the egress of the tunnel have to be further dedicated to that tunnel so that lightpaths can be grouped or de-grouped at both ends. The number of wavelength-switching ports dedicated to the tunnel at the two ends of the tunnel is equal to the number of the wavelengths that the tunnel carries. We say that a tunnel is *brought up* if wavelength-switching port at the both end are dedicated to the allocated tunnel. Wavelength-switching ports at the two ends of the tunnel can be *freed* when there is no lightpath traversing it. The advantage of using MG-OXC is the cost reduction in the size of switch fabric. Fig.2 illustrates an example of the saving.

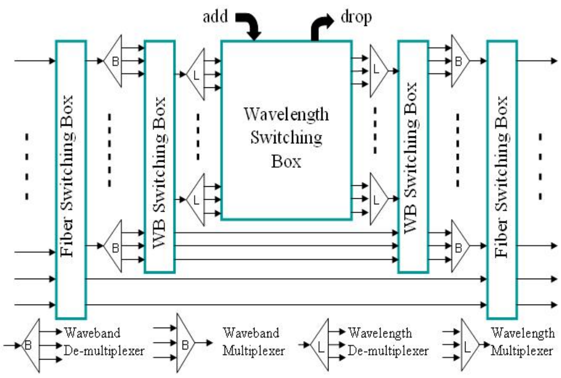


Fig. 1. Architecture of an MG-OXC

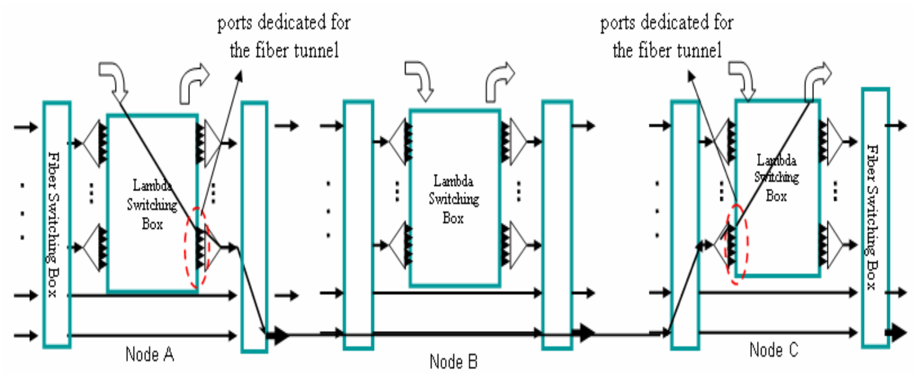


Fig. 2. Advantage of MG-OXC

In this thesis, we make the following assumptions. We assume that each directional link between two nodes consists of F fibers in which F_1, F_2, and F_3 fibers are assigned as fiber-, waveband-, and wavelength-switching fibers respectively (i.e. $F = F_1 + F_2 + F_3$). Accordingly, the number of ports of a node is dependent on its node degree. That is, for example, for a node i with node degree Δ_i, there are $F_3 \cdot \Delta_i \cdot |W|$ wavelength-switching ports for that node, where W is the set of wavelengths in a fiber. We also assume that each node is equipped with sufficient wavelength conversion capability in the wavelength-switching layer. Therefore, a lightpath in the wavelength-switching layer can be converted into any other wavelength if necessary. However, waveband conversion is not assumed, and therefore waveband continuity still has to be maintained. We also assume that a tunnel can only traverse on the shortest path from its ingress node to its egress node.

1.2 Tunnel Allocation and Protection Problem

Although applying MG-OXC can reduce network costs, some problem also arise. Tunnels complicate the routing and wavelength assignment (RWA) problem and should be allocated carefully to achieve higher network performance. Additionally, the protection problem in MG-OXC networks should also be examined, since it has not been intensively studied. This work investigates problems related to MG-OXC networks, including the tunnel allocation problem and the protection problem. The remainder of this thesis is organized as follows.

In chapter 2, we consider the problem of routing and wavelength assignment (RWA) with tunnel allocation in MG-OXC networks. Given a set of static lightpath requests, our problem is to (a) allocate a set of fixed-length tunnels (b) find routes from the source nodes to their respective destination nodes, and (c) assign wavelengths to theses route. The objective here is to minimize the blocking probability. Furthermore, we extend our work for the dynamic RWA problem. Given a historical traffic matrix, the dynamic RWA problem is how to build a set of tunnels off-line to accommodate the future dynamic lightpath requests in such a way that the blocking probability can be minimized. In order to utilize the wavelength ports and fibers efficiently, each tunnel established should follow a tunnel length constraint which could be equal to the average network hop distance. Based on this criterion, a novel graph model is proposed [7] in which edges are added only for the node pairs whose hop distance follow the tunnel length constraint to form an auxiliary graph.

We further analyze the impact of tunnel length on blocking rate based on the hypothesis of fixed tunnel length constraint in chapter 3. This hypothesis occurred originally in [1], but the authors didn’t explain its motivation clearly. A blocking probability model used Erlang loss formula is provided to estimate the performance of tunnel allocation with different tunnel length constraint.

In chapter 4, an efficient fault-recovery protection scheme for the lightpaths was proposed. A segment-based protection scheme, called Tunnel Based Segment Protection (TSP) is proposed to recover the communications interrupted by a fiber cut. Another scheme directly perceived through the senses, called Tunnel based Path

Protection (TPP) is also proposed for comparison. Finally, after the tunnels have been allocated by TSP or TPP, we issue another ILP formulation for the static RWA problem.

Chapter 5 concludes the results of our works and suggests some possible future works.

Chapter 2: Optimal Routing and Wavelength Assignment with Fixed-length Tunnel Allocation

2.1 Introduction

Wavelength-division-multiplexing (WDM) networks have emerged as a method of providing Terabits-per-second capacity for ever-increasing bandwidth demands. Such a network is composed of optical cross-connects (OXCs) interconnected by fiber links, with each fiber supporting tens to hundreds of wavelength channels. End users in the network communicate with each other via one or several all-optical channels, i.e., lightpaths, with transmission rate ranging from one to tens of Gigabits per second.

Although increase in number of wavelength channels and fibers between node pairs may increase the available capacity, this may cause a scalability problem in maintenance and manufacturing of the optical cross-connects (OXCs). An effective way of handling this problem is to bundle a group of consecutive wavelength channels together and switch them as a single unit on a specific route to reduce the required resources of intermediate cross-connects along the route. The tunnel-like passage created by the bundled wavelength channels is defined as a waveband/fiber tunnel. Wavelengths in a tunnel must be switched together except at the two ends of the tunnel. Nodes that support such multigranularity switching, e.g. wavelength, waveband and fiber-switching, are termed hierarchical cross-connects or multigranularity optical cross-connects (MG-OXCs).

The research topics about MG-OXCs can be categorized into (a) being given the network resources and minimizing the blocking probability of the coming requests, and (b) the dimension of the network resources when given the set of traffic requests. In [2], the merits of hierarchical OXC, or MG-OXC, were summarized such as small-scale modularity, reduced cross-talk, and the reducing of complexity. [3] show that the number of ports required when grouping of consecutive lightpaths were applied to the network could be significantly reduced. In [1], a novel switching architecture, MG-OXC, was proposed to minimize the blocking probability for the dynamic requests given the limited network resources. In [4], which employs a two-stage scheme of waveband and wavelength, an integer linear programming (ILP) formulation and a heuristic are given that aim to minimize the size of optical switch matrix under the minimum link loading. However, the model suffers from the defect that only lightpaths with the same destination can be grouped in. In [5], both ILP and heuristic were given to dimension the needed ports by grouping lightpaths with any sources and any destinations. Continuing with [5], [6] further compares Single-Layer MG-OXCs and Multi-Layer MG-OXCs under both off-line and on-line traffic. In [8], the authors try to expand the traditional OXCs for the growing traffic demand by attaching waveband- and fiber-switching boxes to the traditional OXCs. They formulate the problem into a constraint programming (CP) and give an ILP-based heuristics to solve the problem.

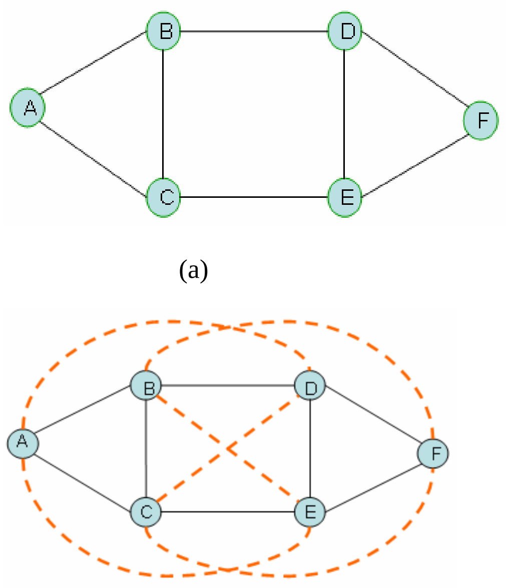
This chapter considers the following network design problems. In static RWA problem it is assumed that set of lightpath requests to be set-up in the network is known initially. Given the fixed amount of network resources, the objective here is to minimize the blocking probability for routing and wavelength assignment problem with fixed-length tunnel constraint. In dynamic RWA problem lightpath requests between source and destination pairs are set up on demand. Given the fixed amount of network resources and a historical traffic matrix that the dynamic requests will follow, the objective is to determine a set of tunnels off-line such that the blocking probability of the upcoming traffic requests is minimized. The heuristic Capacity-Balanced Static Tunnel Allocation (CB-STA) [1] has been proposed and it restricts that tunnels are required to follow a length constraint in order to utilize the wavelength-switching ports efficiently. CB-STA first estimates the amount of traffic traveling through each node by routing the historical traffic matrix in the network. Then the nodes with maximal traffic going out and coming in are selected repeatedly for tunnel allocation. However, since CB-STA does not consider the tunnel length constraint when picking such node pairs, only a few of the selected pairs for tunnel allocation comply with the length constraint. Therefore, a makeup process at last has to be performed to fully exploit the remaining capacity.

In our prior work [7], we proposed a novel auxiliary graph model that aptly incorporates the tunnel length constraint to facilitate solving tunnel allocation problem in MG-OXC networks. The heuristics Weighted Tunnel Allocation (WTA) and Port-Constraint Weighted Tunnel Allocation (PC-WTA) were proposed based this auxiliary graph model and were proved through simulation to show that they outperform CB-STA. In this paper, we extend the auxiliary graph model to a layered one and based on which an ILP formulation is presented to achieve optimal solution under the tunnel length constraint. We conduct the simulation that compares the performance of CB-STA, WTA, PC-WTA, and ILP using small to medium sized network topologies, since for the large sized network topology, the ILP takes an intolerable amount of computation time.

The remainder of this paper is organized as follows. In Section 2.2, we describe the auxiliary graph model [7] for the fixed-length tunnel allocation. In Section 2.3, we first extend the auxiliary graph model to a layered one and then based on which we provide our ILP formulation. Section 2.4 shortly describes WTA and PC-WTA, which are developed based on the auxiliary graph. Section 2.5 shows the simulation results.

2.2 Auxiliary Graph Model

As we mentioned in Section 2.1, we restricted that tunnels allocated in the MG-OXC networks should follow the tunnel length constraint to efficiently utilize the network resources. More specifically, if the value of the length constraint is set too small, the wavelength-switching ports can be used up easily. On the other hand, if it is set too large, the routing flexibility would be decreased since most of the lightpath requests are shorter than the tunnels. In our study we set the tunnel length constraint D to the minimum integer that is larger or equal to the average network hop distance. Apparently, following the tunnel length constraint, we can see that only the node pairs with their shortest hop distance equal to D could be possibly allocated tunnels. Based on this criterion, in [7] we proposed an auxiliary graph model that aptly incorporates the tunnel length constraint to facilitate solving tunnel allocation problem in MG-OXC networks. Given the network topology, the auxiliary graph is constructed by simply adding edges for those node pairs whose shortest hop distance comply with the tunnel length constraint. Fig. 3 gives an example how the auxiliary graph is constructed where Fig. 3(a) is the original network topology with average hop distance equal to 1.53, i.e., D = 2 and Fig. 3(b) is the corresponding auxiliary graph, where dashed link are inserted representing the tunnels that could be allocated between the incident nodes.



(a)

(b)

Fig. 3 An example of auxiliary graph. (a) Network topology with tunnel length constraint D = 2. (b) Corresponding auxiliary graph.

In the next section, we will extend the proposed auxiliary graph model to the layered auxiliary graph model. Based on such layered graph, we propose an ILP formulation to the tunnel allocation problem.

2.3 Layered Auxiliary Graph and ILP Formulation

The given network can be described as follows. G (V, E) represents the network topology where V is the set of nodes and E is the set of directional links. A directional link contains $F = F_1 + F_2 + F_3$ fibers. A fiber contains $|W|$ wavelengths or $|B|$ wavebands, where W is the set of wavelengths in a fiber and B is the set of wavebands in a fiber. Our objective is to satisfy as many lightpath requests specified by a given traffic matrix Λ as possible. Our formulation can jointly determine the routing path of each established lightpath and the set of tunnels that are allocated and brought up. For the network without wavelength conversion, the wavelength assignment of each lightpath can be extended from our formulation. In the following sections, we first describe the construction of the corresponding layered auxiliary graph which our formulation is based on and then give the ILP formulation.

A. Layered Auxiliary Graph

A layered auxiliary graph is denoted by G' (V', E'). To avoid confusion, we use the terms *node* and *link* to represent a vertex and an edge, respectively in G (V, E), and we use the terms *vertex* and *edge* to represent a vertex and an edge, respectively in G' (V', E'). The construction of G' is described as follows. For each node $i \in V$, replicates it three times in G' and denote them as v_i^L, v_i^B, and v_i^F respectively, where the superscript L, B, and F indicate that they are in the wavelength-switching, waveband-switching, and fiber-switching layer, respectively. That is, $V' = V^F \cup V^B \cup V^L$, where $V^F = \{ v_i^F \mid i = 1 \sim |V|\}$, $V^B = \{ v_i^B \mid i = 1 \sim |V|\}$ and $V^L = \{ v_i^L \mid i = 1 \sim |V|\}$. We refer to waveband-switching layer and fiber switching layer together as the tunnel layers.

For each node $i \in V$, an additional edge is created to connect between each pair of the vertices v_i^L and v_i^B, and v_i^B and v_i^F in G'. These edges are called *inter-layer edges*, meaning that the lightpaths can traverse between tunnels and wavelength-switching layers. For every link $(l, m) \in E$, there are F_3 number of edges from v_l^L to v_m^L. These edges correspond to the number of wavelength-switching fibers from node l to node m. For every node pair (i, j) in G that complies with the tunnel length constraint, there are $F_1 \cdot h_{ij}$ number of edges from v_i^F to v_j^F and $F_2 \cdot h_{ij} \cdot |B|$ number of edges from v_i^B to v_j^B, where h_{ij} is the number of shortest paths in G from node i to node j and B is the set of wavebands in a fiber. Each of these edges represents a tunnel that could possibly be traversed by the lightpaths. In the layered auxiliary graph G' (V', E'), we refer to all the additional edges in the tunnel layers as *tunnel edges*. Obviously, the final construction of the auxiliary graph is a multigraph graph. Thus, we use a three-tuple notation (v_l, v_m, p) to distinguish the different edges between vertices v_l and $v_m \in V'$. We denote edges in wavelength-switching layer, waveband-switching layer, fiber switching layer, and inter-layer edges as E^L, E^B, E^F and E^I, respectively. That is, $E' = E^L \cup E^B \cup E^F \cup E^I$.

Fig. 4 illustrates how a layered auxiliary graph is constructed assuming that $F_1 = F_2 = F_3 = 1$, $|B| = 2$, and tunnel length constraint $D = 2$. The colored edges in Fig. 4 represent the potential fiber and waveband tunnels that could be brought up in the optimization process. There are, for example, four edges from v_2^B to v_3^B since there are two shortest paths, i.e., 2-1-3 and 2-4-3, from node 2 to node 3 ($h_{23} = 2$) and two wavebands in a fiber ($|B| = 2$). The dashed edges in tunnel layers just show the physical topology and do not really exist in the graph.

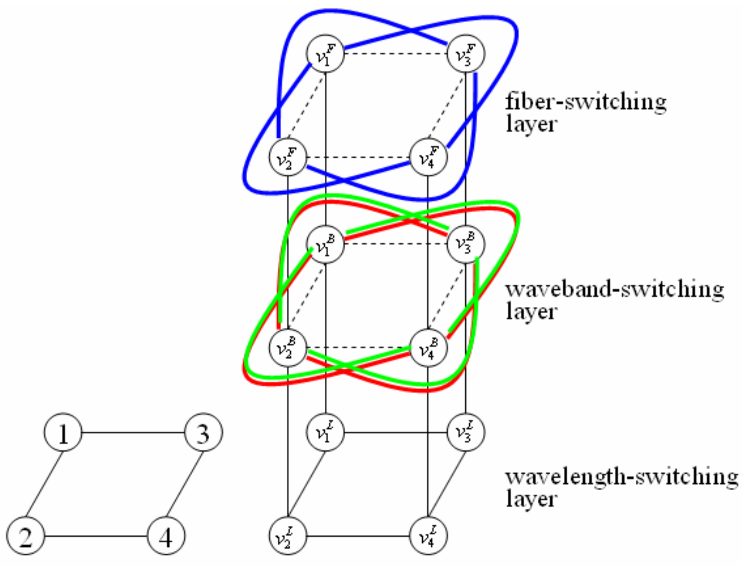


Fig. 4. Illustration of constructing a layered auxiliary graph. A network topology and the corresponding layered auxiliary graph.

B. ILP Formulation

The following notations are invariables. R = {(s_n, d_n) | n = 1… $\sum_{i,j\in V}\Lambda_{ij}$, s_n, d_n ∈ V} represents a set of source-destination pairs requesting lightpath connections. $WS(v_i, v_j, p)$ = {w | w ∈ W is the wavelength within the tunnel (v_i, v_j, p), (v_i, v_j, p) ∈ $E^F \cup E^B$ }. $PF_{(l,\, m)}$ = {(v_i, v_j, p) | (v_i, v_j, p) ∈ E^F is a fiber tunnel and its corresponding physical path passes through link (l, m)}. $PB_{(l,\, m,\, b)}$ = {(v_i, v_j, p) | (v_i, v_j, p) ∈ E^B is a waveband b tunnel and its corresponding physical path passes through link (l, m)}. The variables used in the formulation are defined as follows. Notably, they are all binary variables. $f(s_n, d_n)$, n = 1 ~ |R|, is 1 if a lightpath request (s_n, d_n), is satisfied, and 0 otherwise. For each edge (v_i, v_j, p) ∈ E', $x^{n,w}_{v_i,v_j,p}$, n = 1 ~ |R|, $w \in WS(v_i, v_j, p)$, is 1 if the n-th lightpath request traverses edge (v_i, v_j, p) in wavelength w, and 0 otherwise. For each tunnel edge (v_i, v_j, p) ∈ $E^F \cup E^B$, $M_{v_i,v_j,p}$ is 1 if the edge is brought up, and 0 otherwise. The optimization is formulated as a 0/1 ILP shown below.

Maximize $\sum_{(s_n,d_n)\in R} f(s_n, d_n)$ (1)

Subject to

$$\sum_{(v_i,v_j,p)\in E',\, w\in WS(v_i,v_j,p)} x^{n,w}_{v_i,v_j,p} - \sum_{(v_j,v_k,p)\in E',\, w\in WS(v_j,v_k,p)} x^{n,w}_{v_j,v_k,p} = \begin{cases} f(s_n, d_n) & \text{, if } v_j = v^L_{d_n} \\ -f(s_n, d_n) & \text{, if } v_j = v^L_{s_n} \\ 0 & \text{, otherwise} \end{cases} \quad (2)$$

, for $(s_n, d_n) \in R$ and $v_j \in V'$

$$\sum_{(s_n,d_n)\in R} x^{n,w}_{v_i,v_j,p} \le 1 \text{ , for } (v_i, v_j, p) \in E^L \cup E^B \cup E^F \text{ and } w \in WS(v_i, v_j, p) \quad (3)$$

$$\sum_{w\in WS(v_i,v_j,p),(s_n,d_n)\in R} x^{n,w}_{v_i,v_j,p} \ge M_{v_i,v_j,p} \text{, for } (v_i, v_j, p) \in E^B \cup E^F \quad (4)$$

$$|W| \cdot M_{v_i,v_j,p} \geq \sum_{w \in WS(v_i,v_j,p),(s_n,d_n) \in R} x_{v_i,v_j,p}^{n,w} \text{ , for } (v_i, v_j, p) \in E^B \cup E^F \tag{5}$$

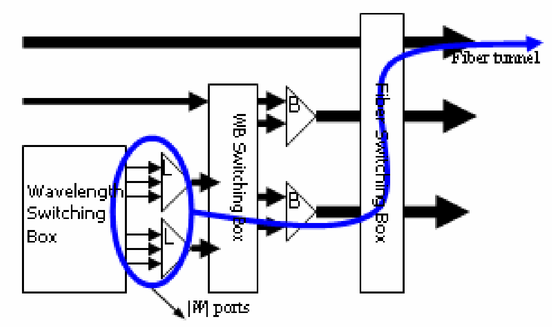
$$\sum_{(v_i,v_j,p) \in PF_{(l,m)}} M_{v_i,v_j,p} \leq F_1 \quad \text{, for } (l,m) \in E \tag{6}$$

$$\sum_{(v_i,v_j,p) \in PB_{(l,m,b)}} M_{v_i,v_j,p} \leq F_2 \quad \text{, for } (l,m) \in E \text{ and } b \in B \tag{7}$$

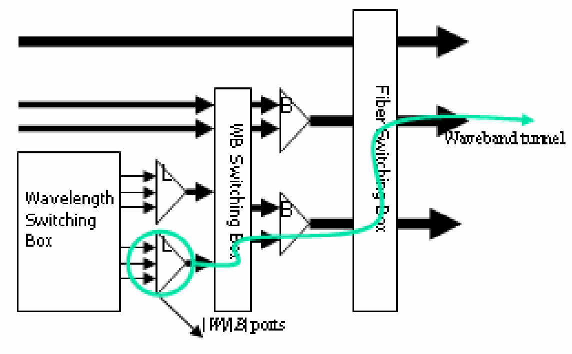
$$\begin{aligned} &|W| \times \sum_{(v_j^F,v_k^F,p) \in E^F} M_{v_j^F,v_k^F,p} + \frac{|W|}{|B|} \times \sum_{(v_j^B,v_k^B,p) \in E^B} M_{v_j^B,v_k^B,p} \\ &+ \sum_{(v_j^L,v_k^L,p) \in E^L,(s_n,d_n) \in R, w \in W} x_{v_j^L,v_k^L,p}^{n,w} \leq F_3 \cdot |W| \cdot \Delta_j \quad \text{, for node } j \in V \end{aligned} \tag{8}$$

$$\begin{aligned} &|W| \times \sum_{(v_i^F,v_j^F,p) \in E^F} M_{v_i^F,v_j^F,p} + \frac{|W|}{|B|} \times \sum_{(v_i^B,v_j^B,p) \in E^B} M_{v_i^B,v_j^B,p} \\ &+ \sum_{(v_i^L,v_j^L,p) \in E^L,(s_n,d_n) \in R, w \in W} x_{v_i^L,v_j^L,p}^{n,w} \leq F_3 \cdot |W| \cdot \Delta_j \quad \text{, for node } j \in V \end{aligned} \tag{9}$$

The objective function (1) aims to satisfy as many lightpath requests as possible. Equation (2) stipulates the flow conservation constraint for a specific lightpath request. Equation (3) shows that each wavelength in each edge $(v_i, v_j, p) \in E^F \cup E^B \cup E^L$ can be used just once. Equation (4) says that a tunnel won't be brought up if there's no lightpath traversing through that tunnel, while Equation (5) says that a tunnel must be brought up if any lightpath traverses it. Equation (6) constrains that the number of fiber tunnels traversing a link cannot exceed the number of fiber-switching fibers on that link. Similarly, equation (7) constrains that the number of waveband tunnels of a waveband b traversing a link cannot exceed the number of waveband-switching fibers on that link for all $b \in B$. Equation (8) and (9) describe the wavelength-switching port constraint on the egress side (output port) and ingress side (input port) of an OXC node, respectively, where Δ_j is the node degree of node j in G. The first term on the left-hand side of equation (8) summarizes a node's wavelength-switching output ports consumed by the fiber tunnels that start from that node. Similarly, the second term summarizes those consumed by the waveband tunnels. The third term summarized those consumed by the lightpath bypassing or starting from that node. The summation of these three terms cannot exceed the number of wavelength-switching output ports that the node has. In the same way, equation (9) indicates that the summation of a node's wavelength-switching input ports consumed by the fiber tunnels and waveband tunnels that ending at that node, and the lightpath bypassing or ending at that node should not exceed the number of wavelength-switching input ports. Fig. 5 illustrates the wavelength-switching output ports consumed by the ingress of a fiber (Fig. 5(a)) and a waveband tunnel (Fig. 5(b)).



(a)



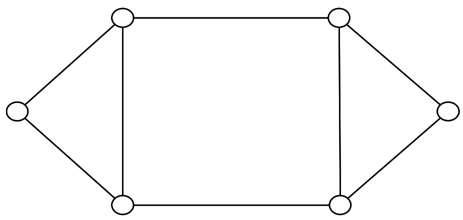
(b)

Fig. 5. Illustration for equation (8). (a) Ingress of a fiber tunnel consumes |*W*| wavelength-switching ports. (b) Ingress of a waveband tunnel consumes |*W*|/|*B*| wavelength-switching ports.

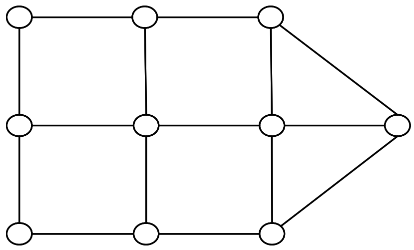
2.4 Auxiliary Graph Based Heuristic Algorithms

In this section, we shortly describe the heuristics WAT and PC-WTA [7], which are based on our auxiliary graph model. In WTA, an auxiliary graph is first constructed (see Fig. 3). After that, to estimate the load that the edges in the auxiliary carry, we temporarily route all the traffic demands on the auxiliary graph. Note that the expected load on the edges connecting the node pairs that comply with the tunnel length constraint now represent the expected load that would flow on the tunnels constructed for them. Then we enter the tunnel allocation stage that repeatedly picks the edge with the maximum expected load and try to allocate a tunnel for it. The success or failure of allocating a tunnel is determined by whether there is sufficient link capacity along any of its shortest paths. The heuristic is ended by a makeup process that tries to utilize any remaining resource that could be allocated tunnels. However, in this paper, we will not perform any makeup process in all heuristics and ILP in order to have fair comparison.

PC-WTA is basically WTA with a slight difference when allocating tunnels. In PC-WTA, a tunnel is successfully allocated for a node pair only if the link capacity along any of its shortest paths and wavelength-switching ports at the ingress and egress nodes of the tunnel are available. This modification is to prevent allocating too many non-critical tunnels such that it would consume wavelength-switching ports efficiently. As expected, the simulation results following will show that PC-WTA performs better than WTA when the wavelength-switching capability is significantly fewer than the resources in the fiber-switching and waveband-switching layers.



(a)



(b)

Fig. 6. Network topologies adopted in our simulation. (a) 6-node network topology. (b) 10-node network topology.

2.5 Simulation Results

The set of tunnel determined by our heuristics can be applied to both static traffic and dynamic traffic. For the static traffic, where all the traffic demands are known in advance, the performance differs as the order in which the requests are routed changes. After we adopt WTA as the major heuristic that determines the set of tunnels, we use the following schemes as the routing sequence to compare the simulation results with the ILP solution. The ILP is solved by LINDO optimizer [19].

- *Random* : the sequence to route the requests is randomly chosen.
- *Shortest Path First* : the request with the shortest hop distance on the network topology from the source to the destination is chosen first to be routed.
- *Longest Path First* : the request with the longest hop distance on the network topology from the source to the destination is chosen first to be routed.

We use the 6-node network topology shown in Fig. 6(a) with $|W| = 4$ and $|B| = 2$. A set of 50 requests are randomly generated among different node pairs.

(F_1)F(F_2)B(F_3)L stands for the experiment with F_1 fibers for fiber-switching, F_2 fibers for waveband-switching, and F_3 fibers for wavelength-switching in each directional link on the network topology. The results are shown in Table I. The numbers in the table are the blocking probability of the total requests. We observe that among the three schemes of routing sequence, Shortest Path First performs best while Longest Path First has the worst performance. Also, the case of 1F1B1L performs better than that of 2F1L due to the better switching flexibility.

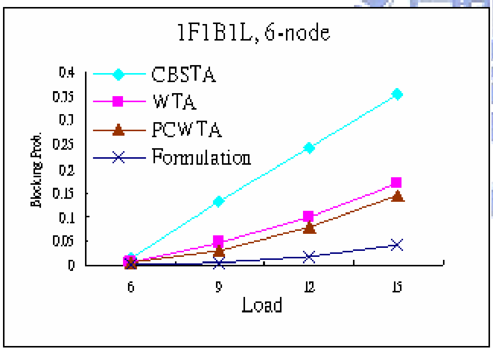
TABLE I

Comparison Of Different Traffic Routing Sequence Under WTA With The ILP Solutions.

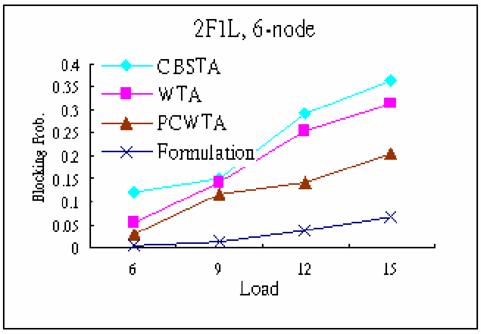
	ILP	WTA		
		Random	Shortest	Longest
1F1B1L	0.12	0.272	0.176	0.348
2F1L	0.12	0.280	0.178	0.360

For the dynamic traffic, we compare the performance of ILP, CB-STA, WTA, and PC-WTA using the small and medium sized network topologies shown in Fig. 6(a) and (b). We assume that $|W| = 4$ and $|B| = 2$. The historical traffic matrix Λ is randomly generated. This traffic matrix is used as the input traffic for the ILP process and the heuristics. Note that the ILP formulation assumes that the traffic is static. Therefore, we will discard the routing information of each request in ILP solution and only take the set of tunnels allocated. The obtained set of tunnels is used to accommodate the dynamic requests. The dynamic traffic is generated with request arrival rate following a Poisson distribution with rate ρ. Source and destination of each request is determined by the probability $\Lambda_{i,j} / \sum \Lambda_{i,j}$. The request holding time is determined by an exponential distribution function with rate 1.

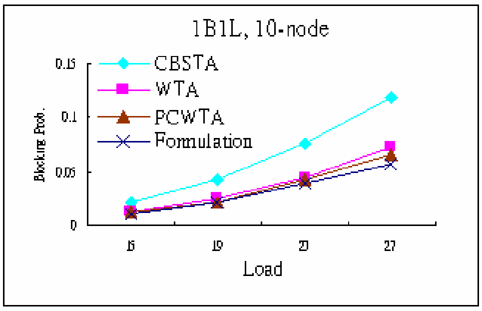
Fig. 7 shows the simulation results. Each datum is derived by running 50000 requests. It can be observed that WTA and PC-WTA outperform CB-STA in both networks. In the 6-node network, PC-WTA outperforms WTA (Fig. 7(a) and (b)) and in the 10-node network, PC-WTA and WTA even perform almost the same as the ILP solution (Fig. 7(c) and (d)). Comparing Fig. 7(a) and (b), we also observe that 1F1B1L performs better than 2F1L, and for Fig. 7(c) and (d), though it is not obvious, 1B1L is slightly better than 1F1L. This is legitimate since the more fibers are dedicated to the fine-grained switching type, the more flexible the routing of the requests is.



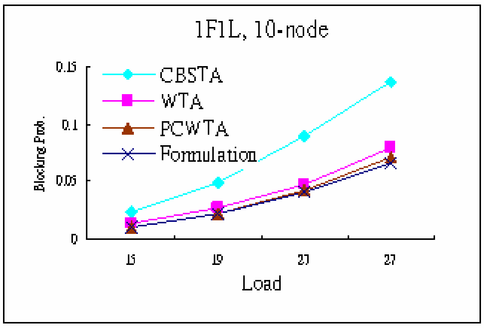
(a)



(b)



(c)



(d)

Fig. 7. Comparison results of CB-STA, WTA , PC-WTA and ILP under different switching type combination and network topologies. (a) 1F1B1L , 6-node network. (b) 2F1L, 6-node network. (c) 1F1L, 10-node network. (d) 1B1L, 10-node network.

Chapter 3: The Impact of Tunnel Length in MG-OXC Networks

3.1 Introduction

Wavelength-division-multiplexing (WDM) networks have emerged as a method of providing Terabits-per-second capacity for ever-increasing bandwidth demands. Such a network is composed of optical cross-connects (OXCs) interconnected by fiber links, with each fiber supporting tens to hundreds of wavelength channels. End users in the network communicate with each other via one or several all-optical channels, i.e., lightpaths, with the transmission rate ranging from one to tens of Gigabits per second. Although increasing the number of wavelength channels and fibers between node pairs may increase the available capacity, this may cause a scalability problem in maintenance and manufacturing of the optical cross-connects (OXCs). An effective way of handling this problem is to bundle a group of consecutive wavelength channels together and switch them as a single unit on a specific route to reduce the required resources of intermediate cross-connects along the route. The tunnel-like passage created by the bundled wavelength channels is defined as a waveband/fiber tunnel. Wavelengths in a tunnel must be switched together except at the two ends of the tunnel. Nodes that support such multigranularity switching, e.g. wavelength, waveband, and fiber-switching, are termed hierarchical cross-connects or multigranularity optical cross-connects (MG-OXCs) as shown in Fig.1. The advantage of using MG-OXC is the cost reduction in the size of switch fabric. Fig.2 illustrates an example of the saving. The OXC we used in this example is a simple two-stage MG-OXC. There is a 2-hop tunnel has allocated between node A and node C, and its advantage is that there are less wavelength-switching ports consumed in

Node B as a bundle of lightpaths routed from node A to node C through node B. Obviously, if the length of a tunnel is longer, it can save even more ports.

Authors [8] claimed intuitively when the tunnel length is too short, although the short tunnels are flexible and easily utilized by most of the lightpaths, the wavelength-switching ports are used up easily since the wavelength-switching ports are required at the ingress and egress nodes of each tunnel. When the tunnel length is too long, although wavelength-switching ports can be greatly saved, the tunnels may not be suitable for the requests since most of the lightpath requests are shorter than the tunnels. However, neither theoretical nor experiment proofs were provided to uphold this claim.

In this chapter, we first establish approximate analytical models for the optical networks with multi-granularity optical cross connect (MG-OXC). We then study the impact of tunnel length on the blocking rate for MG-OXC optical networks with arbitrary topology.

An analytical model for WDM networks with dynamic traffic is proposed in [9]. Such a model assumes independent link loads over the network, and uses the Erlang formula to get the blocking probability in each link. The correlation between two neighboring links on a lightpath has also been proposed in [10]. An iterative procedure is proposed to compute those non-linear equations to obtain the approximate solution. In addition to [9], there is other analytical model for optical network. In [11], authors propose several blocking probability formulations composed of different parameters (path length, switch size, and interference length) to investigate their effect on blocking probability.

We extend those to model the MG-OXC optical network with arbitrary topology. Based on the analytical results, which have proved to be very close to simulation results, obtained from various kinds of network topologies, we find that the best performance on the length of a tunnel is related to the network topology. To put it plainly, we prove that the most suitable length of a tunnel should be the smallest integer greater than the average hop distance as claimed in [8] or the smallest integer greater than the average hop distance plus 1.

The remainder of this paper is organized as follows. In Section 3.2, we describe the network and traffic model in detail. In Section 3.3, an analysis model is proposed to compute blocking probability. Simulation results are shown in Section 3.4.

.

3.2 Network and Traffic Model

Consider the network that has MG-OXCs as described above. We will make some assumptions about the network and traffic model:

1. The network includes N nodes and L directional links. Every node is reachable from the other nodes.
2. Each directional link has F fibers. ($F = F_1 + F_2 + F_3$, F_1 means the num. of fiber-switched fibers which are only used for constructing fiber tunnels. F_2 means the num. of waveband-switched fibers which are only used for constructing waveband tunnels. F_3 means the num. of wavelength-switched fibers). Each fiber has $|W|$ wavelengths and $|B|$ wavebands.
3. Each node is equipped with a limited number of input/output wavelength-switched ports (we will use "ingress/egress port" to replace this term later) and fully wavelength conversion. The initial number of ingress/egress ports in node i is $F_3 \times \Delta_i$ (Δ_i is the degree of node i).
4. Each traffic request (source/destination pair) has a uniform arrival rate in Poisson distribution and service rate in exponential distribution with average service rate 1. The unit of traffic is a wavelength.

The tunnel allocation process we used here is random allocation since the traffic is uniformly distributed. When a tunnel is allocated, we will bind sufficient input/output ports (link capacity) to its two end nodes.

3.3 Analytical Model

Given an offered load, our analysis estimates the blocking probability on a lightpath with a fixed route in a multigranularity cross-connect WDM network. The network blocking probability will be the average of blocking probability of each lightpath request using an iterative procedure. We first consider a link and a node blocking probabilities respectively. In the case of traditional OXC optical networks, a lightpath request between a node pairs will be blocked if there is no wavelength available on every links of the path. However, in the case of MG-OXC optical networks, a lightpath request can be blocked even if a wavelength is available on the every links of the path. It's not because of wavelength continuity constraint, since full wavelength conversion capability is considered here. If there are no ingress ports or egress ports available on the nodes of the path, a lightpath request can be blocked in MG-OXC networks as well. When a tunnel is allocated, a sufficient ingress and egress ports at its two end nodes should be bound to be used by that tunnel. Therefore, unlike traditional OXC optical networks, in which the availability of wavelength of a link implies the availability of ingress/egress ports at the two end nodes; the MG-OXC must take the node blocking probability into the consideration. We summarized the notations which will be used in the following analysis in Table II.

TABLE II. Definition of Notations

$W(i, j)$	Num. of wavelength in link (*i*, *j*)
$T_{in}(i)$	Num. of ingress ports in node *i*
$T_{out}(i)$	Num. of egress ports in node *i*
$\lambda(s,d)$	Traffic load of (*s*, *d*) pair which is given from traffic matrix
$\lambda_l(i, j)$	Approximate traffic load on link (*i*, *j*)
$\lambda_{n,in}(i)$	Approximate load for ingress port in node *i*
$\lambda_{n,out}(i)$	Approximate load for egress port in node *i*
$B_l(i, j)$	Blocking probability for link (*i*, *j*)
$B_{n,in}(i)$	Blocking probability for ingress port in node *i*
$B_{n,out}(i)$	Blocking probability for egress port in node *i*
$p_b(s,d)$	Blocking probability of a lightpath from node *s* to node *d*.
P_B	Blocking probability of whole network

Let $\lambda_l(i, j)$ be the load request for wavelength on link (*i*, *j*), $\lambda_{n,in}(i)$ be the load requests for ingress ports in node *i*, and $\lambda_{n,out}(i)$ be load request for egress ports in egress node *i*. Then, we use the famous Erlang loss formula to compute the blocking probability on each node and link as follows

$$B_l(i, j) = E(\lambda_l(i, j), W(i, j)) = \frac{\dfrac{\lambda_l(i, j)^{W(i,j)}}{W(i, j)!}}{\sum_{k=0}^{W(i,j)} \dfrac{\lambda_l(i, j)^k}{k!}} \qquad (10)$$

$$B_{n,in}(i) = E(\lambda_{n,in}(i), T_{in}(i)) = \frac{\dfrac{\lambda_{n,in}(i)^{T_{in}(i)}}{T_{in}(i)!}}{\sum_{k=0}^{T_{in}(i)} \dfrac{\lambda_{n,in}(i)^k}{k!}} \qquad (11)$$

$$B_{n,out}(i) = E(\lambda_{n,out}(i), T_{out}(i)) = \frac{\frac{\lambda_{n,out}(i)^{T_{out}(i)}}{T_{out}(i)!}}{\sum_{k=0}^{T_{out}(i)} \frac{\lambda_{n,out}(i)^k}{k!}} \tag{12}$$

Here, $B_l(i, j)$, $B_{n,in}(i)$, and $B_{n,out}(i)$ represent the blocking probability on link (*i*, *j*), and ingress and egress ports of node *i* respectively. After tunnels are allocated, the network would add extra logical links to represent the fiber/waveband tunnels. $W(i, j)$ represents the capacity (number of wavelength) of the link (*i*, *j*). $T_{in}(i)$, and $T_{out}(i)$ represent the residual input/output ports on node *i*. We define that a lightpath could be set up successfully only if each link and node of its route has available wavelengths and input/output ports. Then we use the above formulation to model the blocking probability of a specific lightpath(*s*, *d*) route from source node *s* and destination nodes *d*.

$$p_b(s,d) = 1 - \prod_{(i,j)\in path(s,d)} (1 - B_l(i, j)) \times (1 - B_{n,out}(i) \cdot \delta(i, j)) \times (1 - B_{n,in}(j) \cdot \delta(i, j)) \tag{13}$$

Here *path*(*s*, *d*) is a set of links which on the route of lightpath (*s*, *d*). $\delta(i, j)$ is zero if link(*i*, *j*) is a tunnel link and is one otherwise. As a lightpath passing through a tunnel link, it is never blocked due to lack of ports in this link because we have already bound enough ports to the tunnel. As for other wavelength switch links, we must make sure there are enough ports at both ends of the link and one available wavelength on the link. Generally speaking, the term after pi means the probability that all links of the lightpath have enough ports and wavelengths. We then let one be subtracted from this probability; it becomes the blocking probability of the lightpath.

Because we don't know the actual load on each link and node, the general method is to use a historical traffic matrix to deduce the approximate load. It has shown in [12] that a good approximation to compute the load on each link.

$$\lambda_l(i, j) = \sum_{s,d} P_{i,j}^{s,d} \lambda(s,d) \frac{1 - p_b(s,d)}{1 - B_l(i)} \qquad (14)$$

Here $\lambda(s,d)$ is the load of (*s*, *d*) pair obtained from historical traffic matrix and $P_{i,j}^{s,d}$ is the link-path incidence matrix defined as

$$P_{i,j}^{s,d} = \begin{cases} 1 \ , \ link\ i \in path(s,d) \\ 0 \ , \ otherwise \end{cases}$$

The term $\sum_{s,d} P_{i,j}^{s,d} \lambda(s,d)(1 - p_b(s,d))$ represents the load carried by link (*i*, *j*), and it is smaller than the offered load by factor $1 - B_l(i)$ (due to blocking which occurs when a request arrives finding no available wavelengths on link (*i*, *j*)).

Similarly, we can estimate the load on each input/output port of node *j*.

$$\lambda_{n,in}(j) = \sum_{i} \lambda(i, j) \frac{1 - p_b(i, j)}{1 - B_{n,in}(j)} \qquad (15)$$

$$\lambda_{n,out}(j) = \sum_{k} \lambda(j,k) \frac{1 - p_b(j,k)}{1 - B_{n,out}(j)} \qquad (16)$$

Finally, the average blocking probability in the network is

$$P_B = \frac{\sum_{s,d} p_b(s,d)\lambda(s,d)}{\sum_{s,d} \lambda(s,d)} \qquad (17)$$

In order to solve this set of nonlinear equations and find the system blocking probability, we use the following iterative procedure. We define $\lambda_l^n(i, j)$, $\lambda_{n,in}^n(i)$, $\lambda_{n,out}^n(i)$, $B_l^n(i, j)$, $B_{n,in}^n(i)$, $B_{n,out}^n(i)$, $p_b^n(s,d)$, and P_B^n as the values obtained for

$\lambda_l(i,j)$, $\lambda_{n,in}(i)$, $\lambda_{n,out}(i)$, $B_l(i,j)$, $B_{n,in}(i)$, $B_{n,out}(i)$, $p_b(s,d)$, and P_B at the end of the nth iteration. We start with some initial values for $B_l^0(i,j)$, $B_{n,in}^0(i)$, $B_{n,out}^0(i)$, $p_b^0(s,d)$, and P_B^0 be 0. We then apply the following iterative procedure.

1. let $n = 1$
2. Calculate $\lambda_l^n(i,j)$, $\lambda_{n,in}^n(i)$, and $\lambda_{n,out}^n(i)$ by using equations (14), (15), and (16) respectively.
3. Calculate $B_l(i,j)$, $B_{n,in}(i)$, and $B_{n,out}(i)$ by using equations (10), (11), and (12) respectively.
4. Calculate $p_b^n(s,d)$ by using equation (13).
5. Calculate P_B by using equation (17).
6. If the difference between P_B^n and P_B^{n-1} is smaller than a threshold value, stop. Otherwise, set $n = n+1$ and go Step2

There is something that needs to be noticed. The above iterative procedure may not converge to the solution. Other numerical methods like Newton's method [13] can guarantee the convergence to the unique solution. However, the procedure we used here is much simpler, and it converges to the solution in most cases.

3.4 Numerical Results

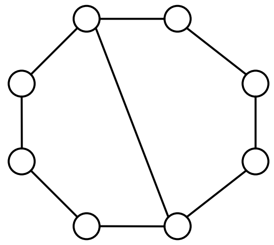
Given a network topology and a traffic matrix, we first allocate the tunnel randomly. The following is our random tunnel allocation procedure.

Step1. Choose a node pair and decide which kind of tunnel (fiber or waveband) randomly according to a probability. The probability is the ratio of the number of waveband tunnels to number of fiber tunnels which should be equal to number of wavebands in a fiber time number of waveband fibers divided by the number of fiber tunnel fibers (F_2 * |B| / F_3).

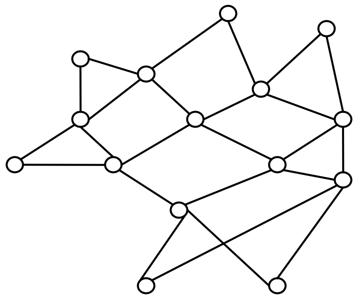
Step2. If the physical hop distance between a node pair matches the tunnel length constraint then go to step3. Otherwise return to step1

Step3. Check the residual input/output ports which need to be bound within tunnel are enough. If there are not enough ports to this tunnel, then discard it and return to step1.

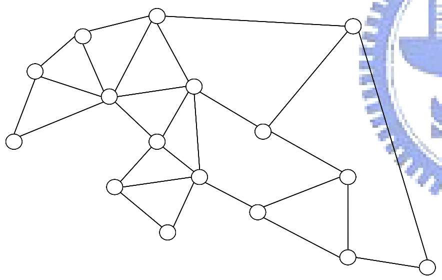
We use the above procedure to allocate tunnels one by one until the number of continuous failures reaches a threshold. In order to prevent wasting the fiber/waveband tunnel fibers, we set the threshold to 500. At the end of the tunnel allocation procedure, we may allocate multiple tunnels between a node pair. For computation simplicity, multiple tunnels with the same kind of capacity will be bundled together between a node pair. For fixed routing, the cost of every link is 1. When the tunnel has allocated off-line and input/output ports have bound to each tunnel, we obtain the numerical results using the blocking probability model described in section Ⅲ and simulation with dynamic traffic respectively. We apply the following four network topologies shown in Fig. 6(a), (b), (c), and (d) with |W| = 40 and |B| = 4. 1F2B2L stands for the networks with one fiber for fiber-switching, two fibers for waveband-switching, and two fibers for wavelength-switching in each bidirectional link on a network topology.



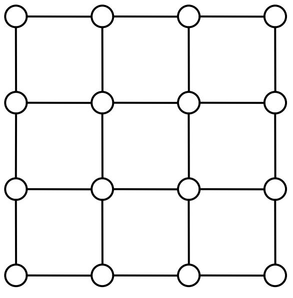
(a) D=2.05



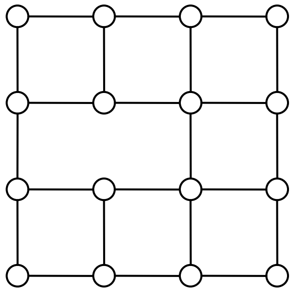
(b) D=2.38



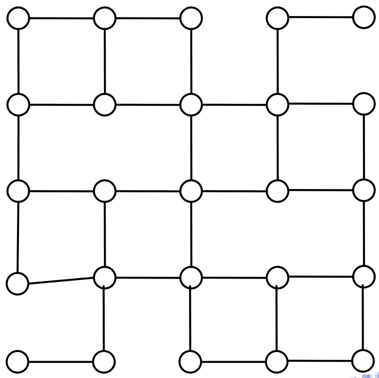
(c) D=2.42



(d) D=2.67



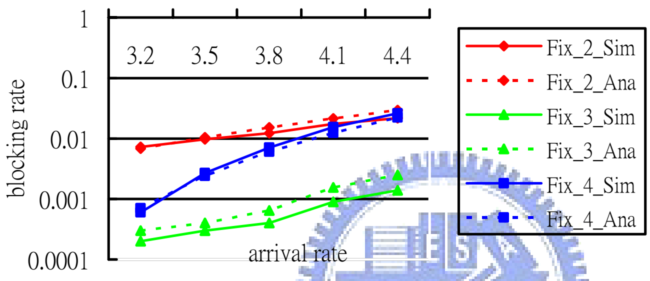
(e) D=2.74



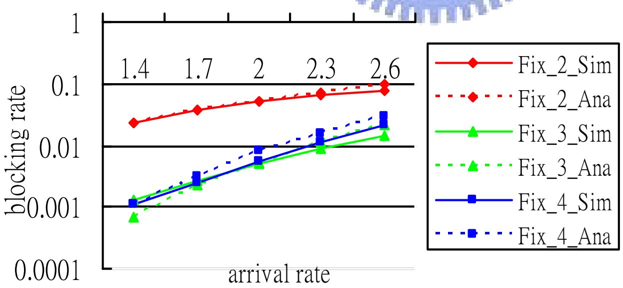
(f) D=3.57

Fig. 8. Network topologies adopted in our simulation. D means the average hop distance.

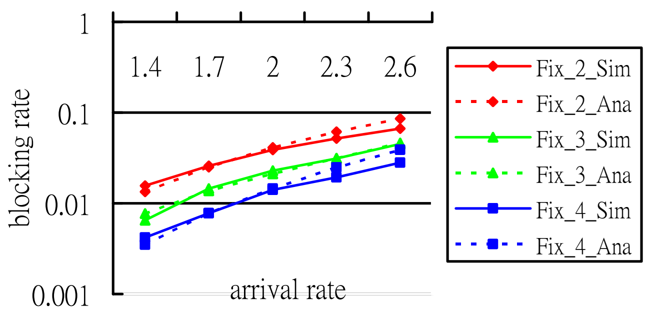
Fig. 9(a), (b), (c), (d), (e), and (f) show the numerical results for network topologies in Fig. 8(a), (b), (c), (d), (e) and (f) respectively. The solid lines represent the simulation results with dynamic traffic. Each datum is derived by running 10000 requests. The dotted lines represent the analysis results of section Ⅲ. In Fig. 9(a) and (b), we observe that the case of fixed 3-hop tunnel length achieves the best performance with the topology of average hop distance equal to 2.05 and 2.38 respectively; even though the performance of fixed 4-hop tunnel length is close to the performance of fixed 3-hop tunnel length in Fig.9(b). In Fig. 9(c), (d), and (e) similarly, we could find the case of fixed 4-hop tunnel length achieves the best performance with topology of average hop distance equal to 2.42, 2.67, and 2.74 respectively. In Fig. 9 (f), we could find the case of fixed 5-hop tunnel length achieves the best performance with topology of average hop distance equal to 3.57. We conclude preliminarily that when the average hop distance of a network topology is closer to next integer (e.g. Fig. 8 (c), (d), (e), and (f)), its tunnel length constraint should be set to the smallest integer greater than the average hop distance plus 1. However, when the average hop distance of a network topology is far from next integer (e.g. Fig. 8 (a) or (b)), the smallest integer greater than the average hop distance may achieve better performance as claimed in [8].



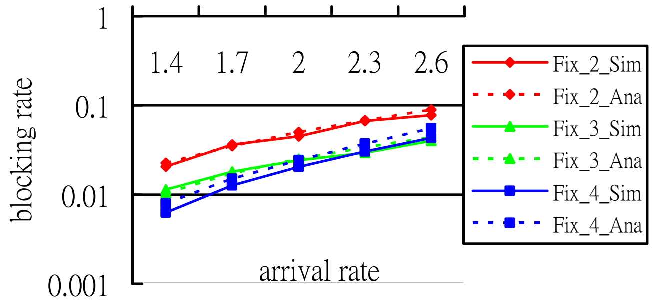
(a)



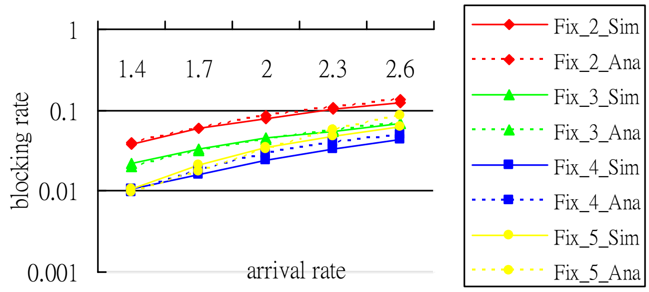
(b)



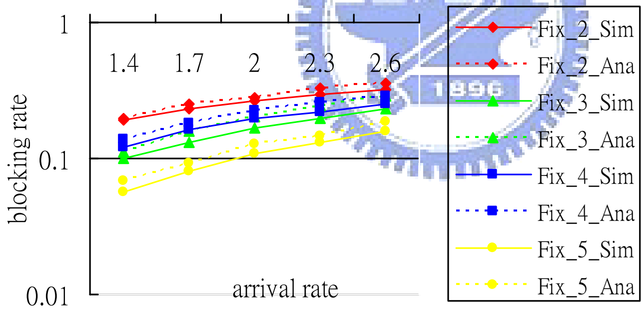
(c)



(d)



(e)



(f)

Fig. 9. Blocking probability of network topologies in Fig.8. (a), (b), (c), (d), (e) and (f) with different tunnel length constraint.

Chapter 4: Tunnel-based Protection Schemes in MG-OXC Networks

4.1 Introduction

The principal idea of MG-OXC networks is to bundle a group of consecutive wavelength channels together and switch them as a single unit on their common sub-path so that the required ports of intermediate cross-connects along the route can be reduced. The bundled channels form the so-called waveband or fiber tunnels in which lightpaths can not be wavelength-switched except at the ends of the tunnels. In this chapter, we aim to provide an efficient fault-recovery protection scheme for the lightpaths in the MG-OXC networks.

In this chapter, we are required to provide protection scheme against a single link failure in the MG-OXC networks. The objective of the protection schemes is to minimize the blocking probability under the constraint that for each request, a working path and protection path must be found simultaneously to guarantee 100% survivability. Since the protection problem has only been considered rarely in the networks with MG-OXC, the mass MG-OXC deployment is at the risk of huge data losses once a link failure occurs. This work thus aims to provide an efficient protection scheme for MG-OXC networks. The protection problem in MG-OXC networks can be divided into two phases, off-line tunnel allocation and finding link-disjoint lightpaths for each incoming request.

Basically, protection schemes can be classified into path protection, link protection, and the compromise of the previous two, segment protection. The protection schemes can be further categorized into shared protection and dedicated protection. In dedicated protection, different backup paths do not share any link in the same wavelength plane. To share the backup resources, the constraint is that two backup paths cannot share wavelengths on the links if their corresponding working paths have common links. Obviously, shared protection utilizes bandwidth more efficiently than dedicated protection. Nevertheless, it is at the expense of recovery time because in shared protection, cross-connects can not be pre-configured to save the reconfiguration time [14].

The protection problem in MG-OXC networks has only been considered in [15], [16] and [17] in the best of our knowledge. The authors of [15] propose a graph-based heuristic that tries to minimize the total number of switch ports in the network, given a set of static connection requests. Our study differs from [15] because we assume that the network resource is already given and the node architecture is the multi-layer MG-OXC proposed in [1] instead of the single-layer MG-OXC. The [16] formulate an ILP to descript the protection problem and a heuristic called waveband/wavelength protection tree (WP-tree) for routing problem. In [17], the authors propose two heuristics PBABL and MPABWL to solve the protection problem in two-layered MG-OXC (waveband and wavelength). The PBABL try to protect the waveband-path by another waveband-path and the MPABWL's working waveband-path could be protected by a wavelength-path. The authors allocate a tunnel to a lightpath request without clear length constraint. It may bring the low tunnel utilization and waste of resource because only few lightpath to use it. Besides, the above they all don't take port constraint into consideration. The object of MG-OXC is to reduce the complexity of traditional OXC. In other words, the port saving is also an important issue. Hence, some link with available wavelength may not work because its two end nodes don't have free wavelength-switched ports.

In [18], the authors define three kinds of scenario none, complete, and partial information to deal with the sharing of backup capacity. None information scenario assume that the network only know the residual (available) wavelength on each link. In this case, the sharing concept is almost can't be achieved. The complete information scenario assumes that it knows the routes for the working paths and backup paths of all the connections currently in progress. Base on the complete information, the manner can easily choose sharing links for a part of backup path. However, the amount of information needed for the complete information model is too large. Finally, sharing with partial information (SPI) assumes the manager knows the working and backup capacity on each link, but don't know the utilized wavelength belong to which request. We choose the sharing with complete information (SCI) scheme to implement in this thesis for convenience.

Basically, the protection scheme in classical optical network has been almost thorough studied. The authors of [19] proposed a matrix-based model (SSR) to solve the spare capacity allocation (SCA) problem. In the SCA problem, the working paths are given. The backup paths need to be found to protect their working paths. The spare capacity reserved by these backup paths are shared in order to minimize the total cost of the spare capacity. In [20], the authors examine the protection time and restoration time based on path and link protection scheme. They also formulate a model for protection switching times for the different protection schemes based on a fully distributed control network. Their conclusion is, path protection provides significant capacity savings over link protection, and shared protection provides significant savings over dedicated protection; while on the other hand, path protection is more susceptible to multiple link failures than link protection, and shared protection is more susceptible to multiple link failures than dedicated protection. In thesis, we used a segment protection scheme which combined the advantage the path and link protection. In [21], the authors proposed a heuristic to avoid the trap problem. That is, the most heuristics (APF, KSP based) may make some mistakes so that they can't find a pair of link-disjoint paths for someone request. But the pair of paths for the request is actually existed. In this thesis, we use a mixed integer linear programming (MILP) to find out each pair of paths for request, and the trap problem would not occur.

This chapter is organized as follows: section 4.2 describes our protection schemes TPP and TSP in MG-OXC networks. The problem of finding a pair of working and backup paths is discussed in section 4.3. Section 4.4 is the simulation design and its result.

4.2 Protection Schemes In MG-OXC Networks

Intuitively, the protection problem in MG-OXC networks can be divided into two phases: 1) off-line tunnel allocation and 2) finding link-disjoint lightpaths for each incoming request. A straightforward solution is to allocate tunnels off-line without protection consideration and then find two link-disjoint lightpaths from source to destination for each incoming request as our future work in [7]. We call this scheme Tunnel Based Path Protection (TPP). Although TPP provides a protection solution for the networks with MG-OXC, the lack of protection consideration in the first phase complicates the finding of link-disjoint lightpaths since two tunnels sharing any common link can not be utilized by a working path and its backup path. Therefore, we propose another scheme called Tunnel Based Segment Protection (TSP). In TSP, a working tunnel is always allocated followed by the allocation of a backup tunnel. Consequently, MG-OXC network protection problem can be formed into one kind of segment protection problem.

A. Tunnel Based Path Protection (TPP)

It should be noted that while allocating tunnels, we only take tunnels that comply with length constraint into account [1]. The length constraint forces all tunnels to have equal length to simplify tunnel allocation. If the value of the length constraint is set too small, the wavelength-switching ports can be used up easily. On the other hand, if it is set too large, the routing flexibility would be decreased since most of the lightpath requests are shorter than the tunnels. In our study we set the tunnel length constraint to the average hop distance.

(a)

(b)

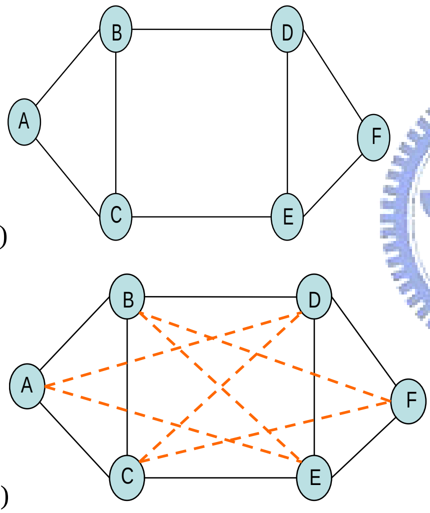


Fig. 10. (a) The original network topology with average hop distance equal to two. (b) The corresponding auxiliary graph.

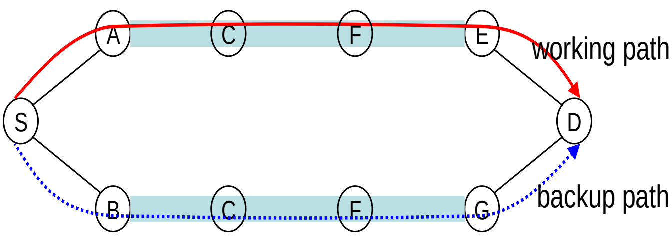


Fig. 11. An example of TPP.

We first transform the physical network topology into an auxiliary graph by adding edges, which we term as potential tunnel edges, between nodes whose shortest hop length follows the length constraint. Fig. 10 demonstrates the construction of the auxiliary graph. After the auxiliary graph is constructed, the historical traffic matrix is temporarily routed on the auxiliary graph with the assumption that the load between each node pair will be equally distributed on all its shortest paths. After finish the routing of all traffics, the total load, or weight, on each potential tunnel edge by this time is just the estimated load between the nodes incident to that edge, and the larger the value the higher priority it gets to be allocated as a tunnel. We then pick up the potential edge with the largest weight, allocate a tunnel for it and decrease its weight for a fixed amount of value. This process is repeated until all the weight of the potential edges are less than or equal to zero. Details of this process can be found in [7].

After the tunnels are allocated on the network, we can start to serve the incoming requests. For each request, both working path and protection path should be found or the request should be blocked. For example, in Fig. 11, two link-disjoint paths are found for request (S, D).

Note that two tunnels for different node pairs on the logical topology may actually traverse the same link on the physical topology, which may cause both tunnels disconnected simultaneously if fiber link failure occurs on that common link. In Fig. 12(a), the two tunnels, A-E and B-F may be used for the working and protection path of a request. But in Fig. 12(b), these two tunnels traverse the same link C-D and may fail simultaneously if a fiber cut occurs on link C-D. Thus, in hierarchical cross-connect network, we must make sure that working and protection paths for a request is physically link-disjoint.

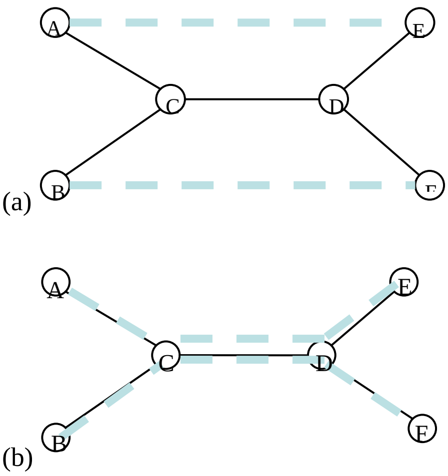


Fig. 12. (a) Two tunnels, A-E and B-F in logical topology (b) Physical route of the two tunnels

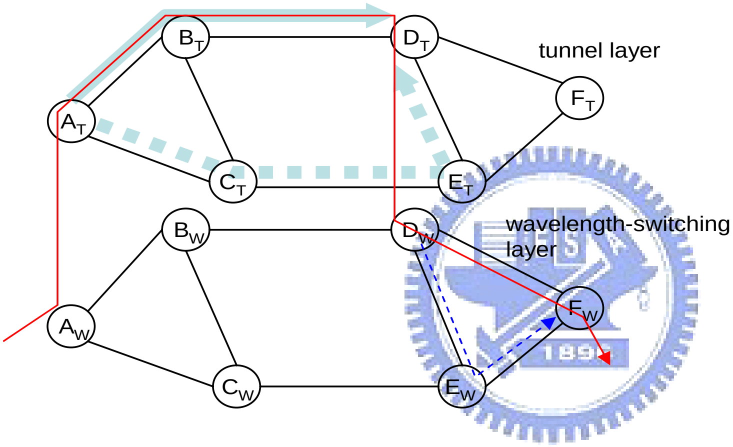


Fig. 13. A layered view for the concept of TSP.

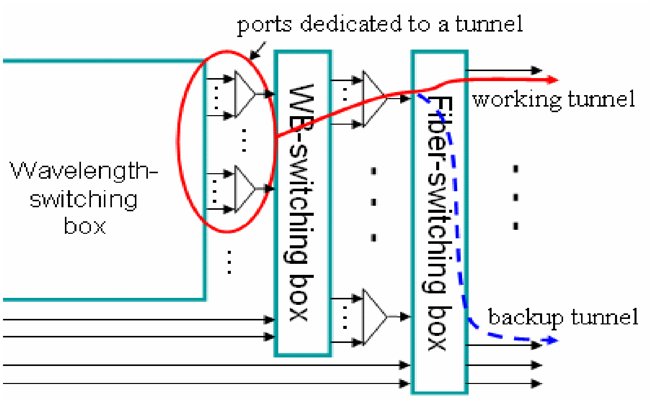


Fig. 14. MG-OXC only reconfigures the fiber-switching box to switch the traffic in working tunnel to protection

B. Tunnel Based Segment Protection (TSP)

TSP operates similarly to TPP except that whenever allocating a tunnel for a node pair, a backup tunnel should also be allocated. Consequently, a working path for a request can be segmented according to the switching types along its route. Since the segments in the tunnel layer are already protected by their backup tunnels, only those segments in the wavelength-switching layer need to be further protected. Fig. 13 gives a layered view of this concept. A working path from node A to node F (A-B-D-F), shown as the red solid line, is divided into A-B-D and D-E, where segment A-B-D is protected in the tunnel-switching layer by backup tunnel A-C-E-D and segment D-E is protected in the wavelength-switching layer by backup lightpath D-E-F.

We deduce that TSP provides better performance than TPP (in terms of blocking probability) for three reasons. The first comes from the intrinsic superiority of resource sharing efficiency in segment protection than in path protection. Second, the conflict of working and protection path would not occur as described in Fig.12, because we can control the allocation of backup tunnel. The corresponding backup tunnel must be physical link-disjoint with its working tunnel. Final, a backup tunnel in TSP can use the same wavelength-switching ports, which is the critical resource in MG-OXC networks, with its working tunnel. Once a link failure occurs and results in breakdown of a working tunnel, we only have to reconfigure the fiber- or waveband-switching boxes on the backup path while leaving the wavelength-switching ports at the two ends of the tunnel unchanged. Fig. 14 shows the port sharing on the ingress side of a working fiber tunnel and its backup tunnel. In contrast to TSP, there is no sharing of wavelength-switching ports between tunnels in TPP, thus a lightpath request may require more wavelength-switching ports.

4.3 Mathematical Programming

After the tunnels has been allocated off-line in the network. Now we want to find a pair of link-disjoint lightpaths for each incoming request. The most popular issue on finding the backup path is the sharing concept. That is, several backup paths can utilize the same fiber link with the same wavelength plane as long as their corresponding working paths are disjointed.

In this section, we formulate the static routing problem in MG-OXC model. This problem can be described more clearly as follows: Given a traffic matrix and a direct auxiliary graph. The auxiliary graph includes wavelength-switching layer edges and some tunnel layer edges. The term wavelength-switching layer edge and tunnel layer edge are simplified to wavelength edge and tunnel edge in the following paragraph. The added tunnel edges are decided by TPP or TSP. The objective here is to satisfy as many as possible connection requests in the traffic matrix. Each request has to find a pair of working and backup path from the source node to the destination node. The wavelength in each link may be occupied to form a part of working or backup path. We assume the network have full wavelength conversion.

There is something need to be noticed. Since a tunnel physically includes several wavelength edges. Some tunnel edges in auxiliary graph look like separated, but they may have some common edges on wavelength switching layer. That is, some separated edges may failure at the same time. Hence, we quote the share risk link group (SRLG) concept to solve this problem. The original definition of SRLG is a group of network links that shared a common resource whose failure will cause the failure of all the links of the group. In this chapter, we only take some tunnels which include the same link to form a SRLG group such as tunnel AE and BF in fig.11.

A. TPP Based Formulation

Base on TPP tunnel allocation, we want to find a pair of SRLG-disjoint path for each connection request. Let *N*, *E* be the set of nodes and edges. E^T , E^W be the set of tunnel edges and wavelength edges. $E = E^T \cup E^W$. *request* is the set of requests. x_{ij}^n is one if the working path of *n*-th lightpath request passes through link *ij*, and zero otherwise. y_{ij}^n is one if the backup path of *n*-th lightpath request passes through link ij, and zero otherwise. The set *g(i,j)* includes all links that may shared a common physical link. $S_{ij}^{uv,n}$ is one if the working path and backup path of *n*-th lightpath request travel link *ij* and link *uv* respectively and zero otherwise. The variable x_{ij}^n, y_{ij}^n and $S_{ij}^{uv,n}$ are 0/1 variable. S_g^{uv} and S^{uv} are positive integer. S_g^{uv} means the backup capacity on link *uv* because a SRLG *g* broken. S^{uv} is the backup capacity on link *uv*. The following is our formulation for static RWA problem, and the objective function is to find as many successful working and backup path for each request as possible.

$$\max \sum_n f(s_n, d_n) \tag{18}$$

$$\sum_i x_{ij}^n - \sum_k x_{jk}^n = \begin{cases} 0 & \text{if } j \neq s_n, d_n \\ -f(s_n, d_n) & \text{if } j = s_n \\ f(s_n, d_n) & \text{if } j = d_n \end{cases} \qquad \forall j \in N, n \in request \tag{19}$$

$$\sum_i y_{ij}^n - \sum_k y_{jk}^n = \begin{cases} 0 & \text{if } j \neq s_n, d_n \\ -f(s_n, d_n) & \text{if } j = s_n \\ f(s_n, d_n) & \text{if } j = d_n \end{cases} \qquad \forall j \in N, n \in request \tag{20}$$

$$x_{ij}^{n} + \frac{\sum\limits_{(i',j')\in g(i,j)} y_{i'j'}^{n}}{\text{LargeNum}} \leq 1 \qquad \forall (i,j)\in E \tag{21}$$

$$\frac{x_{ij}^{n} + y_{uv}^{n} - 1}{2} \leq S_{ij}^{uv,n} \leq \frac{x_{ij}^{n} + y_{uv}^{n}}{2} \qquad \forall (i,j),(u,v)\in E, n \in request \tag{22}$$

$$S_{g}^{uv} = \sum_{n} \sum_{(i',j')\in g(i,j)} S_{i'j'}^{uv,n} \qquad \forall (u,v)\in E, g \tag{23}$$

$$S^{uv} \geq S_{g}^{uv} \qquad \forall (u,v)\in E, g \tag{24}$$

$$\sum_{n} x_{ij}^{n} + \sum_{n} y_{ij}^{n} \leq Capacity(i,j) \qquad \forall (i,j)\in E \tag{25}$$

$$\sum_{n,(j,k)\in\{E-E^{T}\}} x_{jk}^{n} + \sum_{(j,k)\in\{E-E^{T}\}} S^{jk} \leq Outputport(i) \qquad \forall j \in N \tag{26}$$

$$\sum_{n,(i,j)\in\{E-E^{T}\}} x_{ij}^{n} + \sum_{(i,j)\in\{E-E^{T}\}} S^{ij} \leq Inputport(i) \qquad \forall j \in N \tag{27}$$

The equation (18) is the objective function. We want to find as many successful working and backup path for each request as possible. Equation (19) and (20) are the flow constraint for working and backup path. The equation (21) is the SRLG constraint. If link *ij* is a part of working path, the links which belong to the same SRLG can't be the part of backup path for someone lightpath request. The objective of equation (22) is to confirm the variable $S_{ij}^{uv,n}$ is one if the working path and backup path of *n*-th lightpath request travel link *ij* and link *uv* respectively and zero otherwise. The equation (23) computes the demand of backup capacity on link *uv* if someone SRLG *g* broken together. The backup capacity on link *uv* can be shared by different SRLG *g*, so we only to choose a large enough number as the backup capacity on link *uv*. Then, the backup capacity on link *uv* must greater than the maximum demand of all groups. These are described in equation (24). After tunnel allocation, the capacity of every links (tunnel link and wavelength link) and input/output ports on every node are all assigned. Constraint (25), (26) and (27) show the resource constraint.

B. TSP Based Formulation

Base on TSP tunnel allocation, the working tunnel and its corresponding backup tunnel have already been allocated. Hence, we don't leave the backup tunnel edges occurred in the auxiliary graph. For a lightpath request, if its working path passed through a working tunnel, the corresponding backup tunnel should be traveled naturally by its backup path. Then, we only need to find a pair of link-disjoint paths on the wavelength layer. Each pair of working and backup tunnel should be already SRLG-disjoint in TSP scheme. These following constraints only have a little different with the TPP one. Equation (27) constraint the working path and backup path must be link disjoint in wavelength switching layer. Equation (28) restricts the backup path to go through the same working tunnel edges to replace backup tunnel. Other's constraints are the same with the TPP one.

$$\max \sum_n f(s_n, d_n) \tag{24}$$

$$\sum_i x_{ij}^n - \sum_k x_{jk}^n = \begin{cases} 0 & \text{if } j \neq s_n, d_n \\ -f(s_n, d_n) & \text{if } j = s_n \\ f(s_n, d_n) & \text{if } j = d_n \end{cases} \quad \forall j \in N, n \in request \tag{25}$$

$$\sum_i y_{ij}^n - \sum_k y_{jk}^n = \begin{cases} 0 & \text{if } j \neq s_n, d_n \\ -f(s_n, d_n) & \text{if } j = s_n \\ f(s_n, d_n) & \text{if } j = d_n \end{cases} \quad \forall j \in N, n \in request \tag{26}$$

$$x_{ij}^{n} + y_{ij}^{n} \le 1 \quad \forall n,(i,j) \in E^{W} \tag{27}$$

$$x_{ij}^{n} = y_{ij}^{n} \quad \forall n,(i,j) \in E^{T} \tag{28}$$

$$\frac{x_{ij}^{n} + y_{uv}^{n} - 1}{2} \le S_{ij}^{uv,n} \le \frac{x_{ij}^{n} + y_{uv}^{n}}{2} \qquad \forall (i,j),(u,v) \in E, n \in request \tag{29}$$

$$S_{g}^{uv} = \sum_{n} \sum_{(i',j') \in g(i,j)} S_{i'j'}^{uv,n} \qquad \forall (u,v) \in E, g \tag{30}$$

$$S^{uv} \ge S_{g}^{uv} \qquad \forall (u,v) \in E, g \tag{31}$$

$$\sum_{n} x_{ij}^{n} + \sum_{n} y_{ij}^{n} \le Capacity(i,j) \quad \forall (i,j) \in E \tag{32}$$

$$\sum_{n,(j,k) \in \{E-E^{T}\}} x_{jk}^{n} + \sum_{(j,k) \in \{E-E^{T}\}} S^{jk} \le Outputport(i) \quad \forall j \in N \tag{33}$$

$$\sum_{n,(i,j) \in \{E-E^{T}\}} x_{ij}^{n} + \sum_{(i,j) \in \{E-E^{T}\}} S^{ij} \le Inputport(i) \quad \forall j \in N \tag{34}$$

4.4 Simulation Results

We evaluate the performance of TPP and TSP via simulation using a 6-node and 16-node topology (Fig15 (a) and (b)). Because the high complexity of ILP formulation, we only use the 6-node topology to examine. The simulation environment is 1F1L and W=4. For the static traffic, Fig. 16 shows the simulation result. The horizontal axle is the number of request, and the vertical axle is the blocking probability. The TSP always outperforms TPP in all cases. And the ILP always outperforms the heuristic which follows the Dijkstra's algorithm.

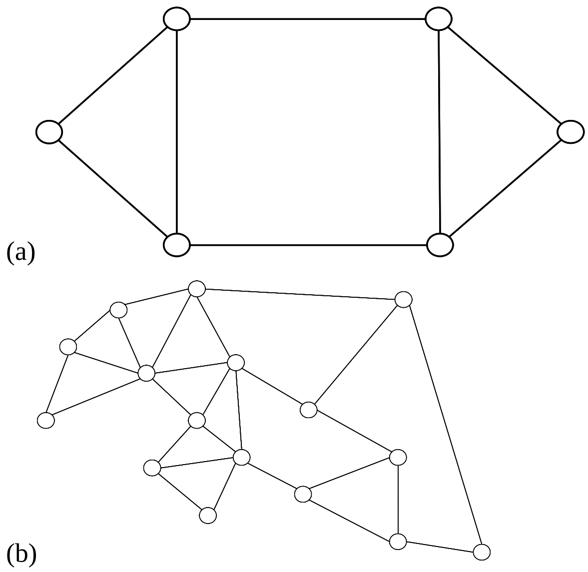


Fig. 15 Network topologies adopted in this simulation. (a) 6-node network topology. (b) 16-node network topology.

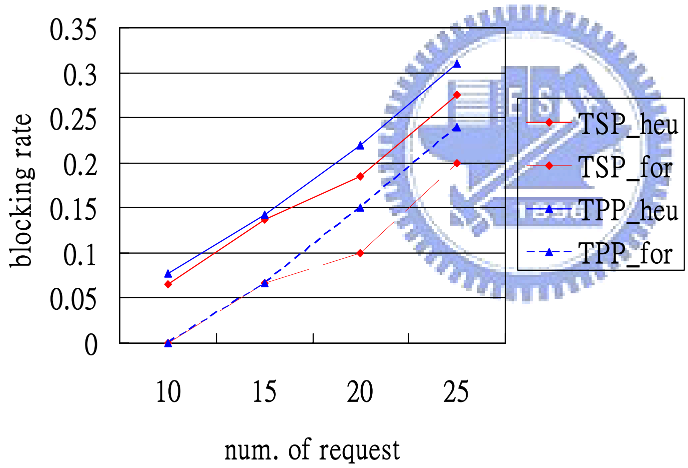


Fig. 16 the blocking rate among different protection schemes

Chapter 5: Conclusions

The problem of RWA with tunnel allocation in the MG-OXC networks is considered by us first. We propose an ILP formulation that gives the optimal solution for the static traffic under the tunnel length constraint. We extend the auxiliary graph model from our previous work to the layered auxiliary graph model to facilitate our ILP formulation. This allows us to consider the RWA and fix-length tunnel allocation sub-problems simultaneously in order to exploit optimal solution. We conduct the simulation experiments to compare the performance between different heuristics and the ILP solution. We first determine a set of fix-length tunnels using WTA, which are based on the auxiliary graph model [7]. Then we adapt one of the routing sequence schemes to route the static traffic over the tunnels. The simulation results show that WTA with the Shortest Path First scheme reaches nearest to the optimal solution. For the dynamic traffic, the results show that WTA and PC-WTA outperform CB-STA significantly. In the 10-node network topology, the performance of WTA and PC-WTA is even compatible with optimal solution. We also observed that PC-WTA outperforms WTA when the number of wavelength-switching ports is small. In MG-OXC networks wavelength-switching ports are critical resources and PC-WTA utilizes the wavelength-switching ports more efficiently.

In chapter 3, we arrive at a preliminary conclusion that the tunnel length constraint is important in terms of blocking performance when we allocate tunnels in MG-OXC optical network. If the length of a tunnel is too long, it consumes more fiber/waveband link recourses, which means fewer tunnels can be established later. On the contrary, if the length of a tunnel is too short, even more tunnels can be established later; since more wavelength switching ports would be consumed with more tunnels, it results that less ports are available on the routing in the future.

Therefore, the tunnel length is a tradeoff between fiber links and switching ports. In this paper, we use both analysis and simulation results to prove that. The numerical results tell us preliminarily that the most suitable length of a tunnel should be the smallest integer greater than the average hop distance as claimed in [2] or the smallest integer greater than the average hop distance plus 1 which depends on that the average hop distance is far from or close to the smallest integer greater than the average hop distance. However, in order to obtain a more general conclusion, we will compare more numerical results for different network topologies especially for networks with larger average hop distance in the future.

In chpapter 4, we investigate the protection schemes for the single link failure in the MG-OXC networks. Path protection based scheme TPP provide a straightforward resolution. However, the absence of taking protection requirement into consideration when allocating tunnels propels us to provide another scheme, TSP, to improve the performance of TPP. In TSP, a backup tunnel is always allocated with a working tunnel. Hence, the working path of a lightpath request can be naturally segmented according to the switching types along its route, with each segment protected in its corresponding layer. In addition to the intrinsic superiority of resource sharing in segment protection than in path protection, TSP also utilizes less wavelength-switching ports for a lightpath request. Simulations are conducted to compare the performance of TPP and TSP. The results show that TSP outperforms TPP in terms of blocking probability, due to the better sharing efficiency of TSP in link capacity and wavelength-switching ports.

Despite the advances in wireless physical-layer technologies, interference is still the main factor of the decreasing in wireless network bandwidth. However, when multiple channels are available, equipping each mesh node with multiple NICs allows the network to use different radio channels simultaneously. Then the available bandwidth can be increased because of the decreasing of interference.

Reference:

[1] P. –H. Ho and H. Mouftah, "Routing and Wavelength Assignment with Multigranularity Traffic in Optical Networks", *IEEE Journal of Lightwave Technology*, Vol. 20, No. 8, Aug. 2002, pp. 1992-1303.

[2] K. Harada, K. Shimizu, T. Kudou, and T. Ozeki, "Hierarchical optical path cross-connect systems for large scale WDM networks," in *Proc. Optical Fiber Communications (OFC'99)*, Vol. 2, Feb. 1999, pp. 356-358.

[3] L. Noirie, M. Vigoureus, and E. Dotaro, "Impact of intermediate traffic grouping on the dimensioning of multi-granularity optical networks," in *Proc. Optical Fiber Communications (OFC'01)*, Vol. 2, March 2001, pp. TuG3.1-TuG3.3.

[4] M. Lee, J. Yu, Y. Kim, C.-H. Kang, and J. Park, "Design of hierarchical crossconnect WDM networks employing a two-stage multiplexing scheme of waveband and wavelength," *IEEE Journal on Selected Areas in Communications*, Vol. 20, Jan. 2002, pp. 166-171.

[5] X. Cao, V. Anand, Y. Xiong and C. Qiao, "Performance Evaluation of Wavelength Band Switching in Multi-fiber All-Optical Networks," *in Proc. IEEE Infocom*, Vol. 3, Mar. 2003, pp. 2251-2261.

[6] X. Cao, V. Anand and C. Qiao, "Multi-Layer versus Single-Layer Optical Cross-connect Architectures for Waveband Switching", *IEEE Infocom'04*, 2004

[7] T. Lo, C. Chen and Y. Chen, "An effect scheme for fixed-length tunnel allocation in hierarchical WDM networks," APOC 2004, November 7~11.

[8] P.-H. Ho, M. T. Mouftah, and J. Wu, "A Scalable Design of Multigranularity Optical Cross-Connects for the Next-Generation Optical Internet," *IEEE Journal on Selected Areas in Communications*, Vol. 21, No. 8, Sept. 2003, pp. 1133-1142.

[9] M. Kovacevic and A. Acampora, “Benefits of Wavelength Translation in All-Optical Clear-Channel Networks,” *IEEE JSAC, vol.14, no.5, June 1996, pp.868-880*

[10] G. Shen, S.k. Bose, T.H. Cheng, C. Lu, T.Y. Chai, “The impact of the number of add/drop ports in wavelength routing all-optical networks” *Optical Networks Magazine, September/October pp.112-122*

[11] R.A. Barry, P.A. Humblet “Models of Blocking Probability in All-Optical Networks with and Without Wavelength Changers” *IEEE JSAC, Vol14, No.5, June 1996*

[12] F.P. Kelly, “Blocking probabilities in large circuit switched networks,” *Adv. Appl. Probability, vol. 18 pp. 473-505, 1986*

[13] A. Girard. “Routing and Dimensioning in Circuit-Switched Networks” *Reading, MA: Addison-Wesley, 1990.*

[14] D. Xu, Y. Xiong, C. Qiao, “Novel algorithms for shared segment protection,” *IEEE JSAC.*, vol. 21, 1320-1331, Oct. 2003.

[15] S. Varma and J. P. Jue, "Protection in Multi-Granular Waveband Networks," *IEEE Globecom* 2004, Dallas, TX, November 2004.

[16] A. C. Varsou, S. Ganguly, and R. Izmailov, “Waveband protection mechanisms in hierarchical optical networks,” *Proc. IEEE HPSR’2003*, pp. 317-322, June 2003.

[17] M. Li, B. Ramamurthy, “Survivable Waveband Switching in WDM Mesh Networks under Dedicated Path-Protection,” IEEE Globecom 2005.

[18] M. Kodialam, T. V. Lakshman, “Dynamic Routing of Bandwidth Guaranteed Tunnels with Restoration,” *IEEE Infocom 2000.*

[19] Yu Liu, David Tipper, “Approximating Optimal Spare Capacity Allocation by Successive Survivable Routing,” *IEEE/ACM TRANSACTIONS ON NETWORKING, VOL.13, NO.1, FEBRUARY 2005.*

[20] S. Ramamurthy, L. Sahastabuddhe, “Survivable WDM Mesh Networks,” *JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 21, NO. 4, APRIL 2003*

[21] Dahai Xu, Yizhi Xiong, Chunming Qiao, Guangzhi Li, “Trap Avoidance and Protection Schemes in Networks with Shared Risk Link Groups,” *JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 21, ISS.11,Nov. 2003*

[22] http://www.lindo.com/