Resources Optimization of Operational Fiber Links & Interconnections for the Merger of Two Optical Networks

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Abstract

Telecommunication networks have been designed to carry voice traffic for decades. With the growth of data traffic in recent years, network operators have constructed substantial amount of fiber optic networks. Multiple telecommunication networks create redundancy in fiber resources. Resources have not been used optimally and revenue has plunged to its lowest since inception. Many network operators are considering co-location and merging in order to reduce cost. Merging two networks can achieve operational savings in redundant fiber links and therefore cost saving to the network operator.

In this thesis, the merger of two networks by adding interconnection fiber links is investigated. Interconnection fiber links are only allowed at the co-located nodes of the two networks. With the additional interconnection links, it is possible to reduce the number of fiber links that are operational while maintaining the full connectivity between any two nodes in the two networks. By suspending some of the fiber links, the operational expenses of those links can be saved. Optimal cost and the number of interconnection links with their optimal locations for the merger of the two optical networks are investigated.

A model is developed for the optimization. The model can be used for the merger of both identical and non-identical networks. The overall costs for various topologies are optimized with respect to different interconnection build costs. It is shown that the merger of two optical networks can reduce more than 50% of operational fiber links, while routing between any two nodes in the two optical networks are maintained. This has been proven through case analysis and analytical results.

The proposed model finds the optimal interconnection locations for different topologies. We analyzed the optimal location for several cases when the number of interconnection fiber links is two and some analytical results are derived. This assists network planners to focus on the optimal locations for interconnection links to be installed.

An algorithm for resource optimization is also developed for the consolidation of two coexisting networks. In all cases after critical interconnection build cost, only two interconnection fiber links are needed. It is shown that the optimization is to find a Hamiltonian path that covers all the nodes in each network or to find a path that contains a maximum number of directly connected articulation nodes with different groupings.

Case analysis results for part of a real China network and other topologies are discussed. Analytical results can be derived for both the minimum number of links required for arbitrary connected networks and the locations of the two interconnections for the merger of two networks. In addition, more comprehensive analysis on the effects of node degree, protection, and traffic demand are discussed. It is conclusive that through the merger of two optical networks substantial saving to the network operator will occur.

摘 要

電信網絡多年來的設計是用作運載聲音等訊息的傳送。近年因數據傳送的發展，網絡運營商鋪設及建造了大量的光纖網絡。多個電信網絡的存在造成大量的光纖資源浪費，資源沒有得到好好的利用，故電信網絡公司收入近年也跌至自成立以來的最低點。許多網絡運營商考慮在同一地點進行合併或資源共用。合併兩個網絡可減少一些光纖的運作，從而網絡運營商可以節省成本。

本論文首先研究在兩個同區的網絡之間，添加互聯光纖鏈接來合併兩個光纖網絡。互聯光纖鏈接只可以添加在同一地區來鏈接兩個網絡。通過這些增加的互聯光纖，運營商可以減少運作光纖的數量，從而節省光纖網絡的運作成本，也同時保持了兩個網絡的任何兩個節點之全面連通。由於有些光纖不需要再使用，這些光纖的運作費用可以大大節省。本論文研究當兩個網絡合併時，如何決定有關之鏈接點數量及其最佳互聯點位置以達致最低網絡運作成本，從而使網絡設計師簡化其設計程序。

本論文設計了一個仿真的模型以方便網絡設計師規劃網絡，此模型可應用於兩個同區或不同區網絡的合併。本論文研究了多種不同的網絡結構在各個不同的互聯光纖造價下如何達致最優的網絡運

作成本。兩個網絡的合併可以減少百分之五十以上光纖的運作，同時可維持任何兩個網絡結點之間的通訊。模擬及分析結果同時證明了這點。

本模型同時可確定各種網絡結構合併之最佳互聯點位置。在只有兩個互聯點的情況之下，鏈接點位置可由理論分析得出。這有助網絡設計師專注與研究互聯點之最佳位置對整個網絡之影響。

經多個案例的研究及分析，隨著互聯光纖造價的提高，兩個網絡的合併最後達至正好需要兩個互聯光纖鏈點。仿真程序也可推斷出此結論。只要網絡設計師找到一個同時涵蓋所有節點的 Hamiltonian 路線。這條路線的兩個端點，便是最佳互聯點。如 Hamiltonian 路線不能找到，設計師可找一條包含最多直接相連的割點的路線，這路線的兩個端點之外的第一個節點便是此網絡其中之一個最佳互聯點。

本論文探討了一個現有的中國光纖網絡及其他結構的網絡。得出模擬結果。理論分析可得出各種結構的網絡所需的最少光纖數目以及最后達致兩個光纖互聯點的最佳位置，從而增強對網絡合併的了解。另本論文也探討了節點運營費及網絡保護方面對網絡合併及互聯鏈接點位置之影響。

最後本論文得出結論，通過合併兩個光纖網絡，網絡運營商將可減少大量光纖的運作，從而節省開支，增加利潤。

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Chapter 1

Introduction

Telecommunication networks have been carrying voice traffic for decades. Network operators have constructed many fiber optic networks with the growth of data traffic. Deregulation and open competition enhance pressure on network operators to compete based upon quality of service (QoS), capacity and operating margin. Overcapacity is the result of over expansion of network resources. Different network operators have constructed networks with similar geographical coverage in more profitable areas. There were no considerations for redundancy of resources. This may result in insufficient demand in sustaining multiple networks [1], [2], [3]. Resources are not being used optimally.

In a competitive market, network operators and vendors often consider takeovers or mergers in order to maximize revenue for survivorship [4]. Operators have also learned that excess operation expenditure and inefficiencies diminish their competitiveness. They are therefore looking forward to migrating to the next-generation architecture in order to achieve savings in operation expenses [5]. A single multi-service optical infrastructure that can support any type of network traffic and any transport technology is desirable to improve efficiency. Operators can maximize their service density and capacity by introducing higher margin services, which can generate more return of investment (ROI) in the future [6]. It is therefore important for operators to look for methods to optimize their network configurations with savings in various network elements (fibers, backbone routers, optical cross-connects, etc.). This results in minimum overall network capital cost and operation expenditure [7]. It is shown in one study that transmission costs account for 34 percent of the average mobile operator's network operating expenses [8]. Field maintenance support constitutes 13%, site rental 15% and technical personnel 29%, respectively. Operation expenditure, if reduced, can mean increased profitability and/or survivorship for the operator. These are all essential elements of the network planning and management that are necessary for the overall network optimization [9]. The network operators need to consider co-existence solutions through co-location, merging, or acquisition in order to reduce cost and generate revenue in the infrastructure overbuilt areas. Cutting the cost of transmission and different forms of infrastructure sharing in Europe and around the world has already taken place between network operators [10], [11]. With the increase in competition, merger of networks is a matter of necessity. The objective of this thesis is to address the issue of merger of two networks from the perspective of an operator and how one can make the best use of existing networks. The optimization involves finding the optimal solution for the merger of two networks, based on a number of constraints.

1.1 Objectives

In order to improve network utilization and reduce network complexity, interconnections of two networks at strategic locations are installed so that traffic can take alternative route. The total number of operational fiber links can be reduced by suspending some of the operational fiber links. Though the redundant fiber links cannot be redeployed to other locations, the operating cost of maintaining those fiber links is reduced. The redundant links can be revitalized when bandwidth demand increases. In this thesis, we present an analysis model for network merger. Through integer linear programming (ILP) simulation, we optimize the locations of the interconnection links, the number of interconnection links, and the savings in fiber links. We will firstly examine a real China dual-ring network and then examine the optimization for different topologies.

The key results in this thesis are as follows. (a) A model for the analysis of optimizing the merger of two networks is developed. The model can also be used for the merger of non-identical networks. Optimal cost after merger of two networks can be identified. (b) The CPLEX program is used for optimization. Under various interconnection build costs, the overall cost is optimized by optimizing the number and location of interconnections to achieve the maximum reduction in the number of operational fiber links (c) Through the study of the real China dual-ring topology, we can understand the effect of interconnection build cost on the resultant operational fiber links and the optimal cost. (d) With the study of various topologies, we can see the effect of topology on the optimized operational links and interconnection links. (e) Extension of the model is studied. The increase in the number of nodes and other real networks are investigated. The effect of node degree and flow cost are analyzed and simulated. Protection of the optimized network and optimization of non-identical networks are also discussed. From these investigations, we can show significant improvements in fiber link savings and therefore ultimate savings to the network operator.

Furthermore, it can be shown that after critical interconnection build cost that the minimum number of interconnection fiber links will be reduced to two by the merger of two networks,. The two interconnection fiber links shall be installed at the nodes, which are one hop from two most apart articulation nodes [12]. This will result in the optimal network and therefore cost saving and efficiency to the operator.

1.2 Thesis organization

The thesis is organized as follows: Chapter 2 describes the present network resource situation, the future optical network, network design issues, related works and literature review. The basic concept about the survivable network design is introduced. The evolution of optical networks and requirements for the design of future optical networks are discussed. Related works and literature review is carried out.

Chapter 3 outlines the optimization model. The model is designed with the intention of identifying an optimal architecture for an optical network with optimized interconnection link or links and therefore optimal operating cost. Traffic flow, node operating cost and required fiber links are variables of importance in terms of minimizing total cost. Assumptions and constraints for the model are discussed in this chapter.

Chapter 4 first describes the optimization of part of a real China network in dual-ring topology. Different topologies are further discussed in this chapter and analysis results are illustrated. Topologies used are circle, tree, bus, and mesh. These topologies are compared with the dual-ring topology and the results of the findings are given.

Chapter 5 gives the analytical results and the discussion for the dual-ring network and other topologies. The results of optimal cost and fiber links required are compared and discussed. The concept of critical interconnection build cost, Hamiltonian path/cycle, and the resultant number of interconnection fiber links with their locations are studied and discussed.

Chapter 6 further discusses the extension of the model. Analysis results to the increase in number of nodes for the dual-ring network and other real networks are also investigated. The relationship between node degree and node cost is taken into consideration. Analytical discussion and case analysis are carried out. It is interesting to find that the critical interconnection build cost has a direct relationship to the operating cost of the operational fiber links. Link protection issues of the optimal network are also discussed in this chapter. Application in the consolidation of non-identical networks is also discussed.

Chapter 7 summaries the contributions and areas of future work. This concludes this thesis and outlines the directions of future research.

Chapter 2

Background and Motivations

2.1 The present network resource situation

Fiber network operators have been vigorously developing and building network in every country for the last 20 years. Operators build and operate their networks independently. There was no consideration for redundancy of resources. Attention was only paid to ensuring certain levels of availability in network elements but not the network itself as a whole. User's expectation has changed this reality; split-second recovery against a major failure is being expected. Optical networks based on wavelength-division multiplexing over fiber optics offer huge point-to-point capacities. Survivability was the selling point for operators in the last decade but the costs of redundancy can be very high compared to a corresponding network designed to serve the working demands under nominal conditions. The costs of a survivable network can be twice the cost of a non-survivable network [12]. Careful choices of architecture and design methods can surely minimize this expenditure.

Government has encouraged open competition on pricing but ignored resource optimizations. Engineers for much of the past two decades have participated in the promulgation of deregulation. It started with air travel in the United States in the late 1970's and onto banking, trucking, railroads, communication and electricity. The results for these deregulations are mixed. Many industries including the telecommunication industry are struggling financially. Many companies are at the verge of bankruptcy. Consumers' expectation for better quality of service (QoS) and reliability cause substantial investment in network infrastructure by the operator.

Each fiber optic transmission system is essentially a fixed point-to-point structure. It bears whatever set of tributary carrier signals or wavelengths that are presented to its inputs, up to its maximum capacity [13]. Through the 1990s the industry vigorously debated ring versus mesh-based principles for survivable transport. Ring systems were relatively easy extensions of existing point-to-point transmission systems and offering fast protection switching. On the other hand, mesh topology offered greater flexibility and capacity efficiency. The choice of architecture is important and depends on the combination of routing efficiency, ease of growth, and service provision flexibility with an ultimate objective of achieving a minimum cost in transmitting capacity for a point-to-point structure.

In recent years, there are not many new "green field" planning. The practical approach is by augmenting or upgrading the existing infrastructure. The addition of new spans will improve the efficiencies of the network as a whole. This addition will also enhance the routing capability for the working demands of the network [13]. In order to achieve this objective, operators are looking into the possibility of selling or leasing to other operators and/or merging networks to reduce the amount of redundancy and therefore the network infrastructure cost. More cost efficient network will improve profitability and increase the chance of survivability to the operator in the present competitive broadband market.

Pricing of providing services has also dropped substantially in recent years. Capital investment in infrastructure therefore is substantially reduced. Operators try to maximize returns from existing assets. Network planning and network optimization have become more critical than ever.

On August 4, 2003, The Hong Kong Special Administration Region Government through the Office of Telecommunications Authority has drafted a guideline for

Hong Kong telecommunications market [3]. The government has taken note of the importance of merging for the telecommunication sectors. The authority needs to assess the competition effects of a merger or acquisition before any approval can be made.

Resources can be better utilized and can minimize duplicated investment in a merged network. Maintenance cost can be reduced in the reduction of operating fiber links. Better throughput on traffic flow, improved traffic reliability, and connectivity can be achieved by a merger of networks.

In China, it has a total area of 9.67M sq. km with a population of 1.3 Billion. It has grown tremendously from 3.5M internet users in December 1999 to over 162M internet users in June 2007 [1]. It is the biggest telecommunication market in the world today and the foreseeable future. Backbone coverage in China poses some key challenges. It covers an enormous geographical area with vastly different terrain and population concentration. The demand for data services is also increasing. In the early years of the optical network in China, operators were investing in networks located in the most populated cities to provide services to end-users. Operators often have duplicated network in the same geographic locations. Overlapping investment in network infrastructures results in increase in the operating cost for the operators. As competition results in a price war between operators, broadband prices drops drastically. Merger of networks or co-location becomes a necessity for the operators. This will result in a more cost effective network and provides protection with alternative routing for the operator. A more reliable network can be achieved.

2.2 The future of optical networks

This section provides an overview of the expectation of the future optical network. In the design of optical networks, network designers need to understand the need of the market. The market is demanding cost-effective solutions for transmitting large volumes of information over long-haul networks [14]. It needs to take into account of both voice and data traffic. The most important development in technology in recent times is the union of information science and telecommunications technologies. Convergence of industries, such as fixed and mobile network operators, ISPs and software providers, means that consumers are expecting new exciting solutions that provide 'any situation, any content and any device' communication [15]. Network planner needs to understand the challenge of balancing the bandwidth demand, driven by the increase in service requirements and the popularity of the Internet. Dense wavelength division Multiplexing (DWDM) offers operators to expand network capabilities to meet this ever-increasing requirement. It increases the network's transmission capabilities, and offers service providers the flexibility to expand capacity in any portion of their networks [16]. In addition to DWDM, the network requires intelligent network nodes that are scalable and simple to integrate. This lowers the financial entry barriers to all optical networks, while raising the efficiency, effectiveness and flexibility of services offered by the network operator. All optical networks allow the operator to maximize the utilization of their own network and allow dynamic network restoration [17].

Traffic patterns are continually changing in real life. Exponential bandwidth demand will occur due to the global deployment of broadband-Internet services and substantial data growth. Current global IP traffic estimates for low- and high-growth scenarios are 22% and 45% per year, respectively. In some geographical areas, the traffic growth can be substantially higher than this average. Asia has 434% growth during the 2003-2004 period [18]. A trend of rapid local network deployment is also being experienced. The volume of data grew from 3 billion to 24 billion gigabytes between 2000 and 2003, with 93% of all data being born digitally [19]. This will increase even more as many traditional services and industries move from analog to digital e.g. TV broadcasting, movie making, and the spread and development of e-services across government, health and security. High performance optical network is desired with the increase expectations from residential and business users as well as the new requirements from scientific users.

A system therefore needs to be flexible to cope with these changes. Next generation elements need to support services architecture and also able to carry out 'network intelligence'. This can be achieved through the use of open interfaces, directories, real-time classification of traffic, and application level classification [20]. Operations Support System (OSS) architecture needs to support flow-through provisioning which includes a complete business, service, network and element management solution. Intelligent networking platform will manage the future business of the operator. Operators need to build robust, cost-effective integrated IP networks that support the delivery of innovative, interactive data, video and voice services. Both hardware and software evolution will lead to increased levels of transparency in the future optical network. Network management becomes more important to the future success of the operator. Optimal minimum cost in infrastructure becomes the key to success for the operator.

2.3 Network Design Issues

The network design is trying to optimize the network resources that carry a certain traffic demand for various network topologies. All traffic flow is routed to its destination at minimum cost to the operator. A better utilization of network resources can minimize operational expenditure (OPEX) for the operator [21]. The designed network decides the most optimal cost network with the lowest operational expenditure for a given requirement. Since capital expenditure (CAPEX) has already been spent on an existing network, this thesis therefore will focus on the minimization of the OPEX for the operator.

Protection is another design issue that is of concern. This ensures QoS of the network. Bandwidth provisioning and overlay networks are commonly done. Fault detection, fault restoration, and various recovery techniques provide protection to the survivable network system. This thesis will examine this issue further in Chapter 6 for our optimal network topology.

Network topology optimization is also an important issue. It needs to cater for traffic demand, protection of the network, infrastructure cost of the network, connectivity of the network, and infrastructure capacities. Optimal topology can result in minimal cost to the operator.

In this thesis, design of a physical topology is not necessary. We are to examine the existing topologies through two identical networks. Traffic will run through all network nodes for a given demand. The question is which fiber links are needed to be operational and where the interconnection fiber links shall be installed. Multi-commodities flow model is commonly used in the design of survivable networks. In this thesis, a mathematical model is designed to take into account for traffic flow, fiber links required, and node cost. This will be further described in Chapter 3.

2.4 Related works and literature review

There are very limited studies in the optimization of merger of two optical networks. We will look at different aspects of related works in the following.

Traffic demand

Various studies have been carried out on forecasting traffic demand [22]. Dynamic traffic demand requirement is discussed in D. Leung's paper [23]. Dynamic traffic pattern is formed to predict traffic flow. Approximate analytic model is also developed to predict the traffic demand matrix based upon a cost constrained and distance dependence for an optical mesh network [24]. Demand model for Internet Service Provider network has been developed from shifts in user behavior, changes in routing policies, and failures of network elements. Traffic demand is firstly defined as a volume of load originating from an ingress link and destined to a set of egress links [25]. These demands are then computed from flow-level measurements at ingress links and reachability information about egress links. Other traffic model in the US has been developed based on the total population, non-production business employees, the number of internet hosts in each city and the distance between two cities. Excess capacity is also allowed for restoration and protection [26]. Other dynamic traffic studies can be found in traffic engineering [27].

Network design

Network design has explored the possibility in installing additional fiber links to all nodes and therefore each node has more incoming/outgoing fibers. A new node configuration can then be worked out. The network can use smaller optical switches and therefore reduce equipment cost while it still maintains small blocking probability [28]. However, this study totally ignores the high cost of installing fiber links in different terrains. It only took into account the fiber link material cost but not the installation cost.

Protection

On the issue of protection, it is generally implemented through overlaying networks, bandwidth over-provisioning, and per-flow queuing and signaling e.g. IP Quality of Service mechanisms such as Class-Based Queuing (CBQ) or Penalty Box algorithms [29]. Most operators will employ the overlay networks approach. Different solutions are proposed for dynamic survivable service provisioning. They are generally done by separating the total capacity into the working and spare capacity. Operators specify the capacity limit on each link based on a single traffic matrix and create a protected working capacity envelope. After optimization, operator chooses the shortest path routing to satisfy this total capacity [30].

Other studies, including full survivability against link failures and support for dynamic traffic demands for future backbone networks are done. A certain minimum capacity is required for each edge to form a generalized survivable network (GSN). A two-phase approach and Lagrangian relaxation approach are used to solve the GSN network design problem [31]. Other self-protection scheme looks at the protection for Ethernet passive optical networks (EPONs) to carry out at the MAC layer. Therefore, this does not induce noticeable computation overhead [32]. Network designers are looking for resilience designs in optical networks. Many designs are based on the standby restoration scheme, thus much duplicated investment has to be incurred by the operator. Since the 1+1 protection is provided, it is the most expensive alternative. Operator needs to provide dedicated protection paths to achieve this 1+1 protection. On the other hand, if we use a hot standby scheme, it will cost much less than 1+1 because of wavelength-regenerator sharing within the network. The disadvantage is the longer restoration time due to the power equalization convergence process for the hot standby scheme [33]. Network designer needs to balance all the advantages and disadvantages for the various schemes to arrive at the best optimal design of a network for the operator.

Fault localization

Other more in-depth studies such as bandwidth allocation for back up paths, fault localization, fault restoration and recovery techniques are studied. Algorithms are developed for efficient bandwidth allocation for back up paths and path failure probability. Fatal failure probability is less than 0.5% as the number of primary paths spans from 1 to 110 [34]. Through monitoring cycles, fault detection mechanism can be developed. Heuristic depth first searching (HDFS) and shortest path Eulerian matching (SPEM) fault detection mechanism are proposed. Meshed optical networks are decomposed into cycles. The two algorithms are compared in terms of node and link wavelength utilization. These algorithms cut more than half of the costs of the transceivers as compared to the conventional fault detection schemes e.g. one-monitor-per-link case [35].

Fault restoration

Fault restoration traditionally is done through a centralized network manager to provide QoS. Distributed fault recovery can be faster and more scalable than centralized fault recovery. Back up route can be pre-established but back up bandwidth is not reserved. This partial path restoration technique can achieve fault recovery but does not require full provision in the fiber links [36].

Green field network design

Network planners have carried out green field network design. Analytical framework has been done to decide on the network's physical architecture in order to achieve minimum cost. The design problems are either solved analytically with the topology design, dimensioning, and routing algorithm as decoupled problems or as joint problems. The optimal node degree depends on the network size; the fiber-switch cost ratio, as well as the number of wavelengths of traffic between each node pairs. Network connectivity is a function of topology and switching fabrics [37].

Summary

Since most operators own single network, network designers tend to analyze single network in terms of traffic demand, additional fiber links to node, protection, fault restoration, QoS, and node connectivity. No due consideration has been given to a merger of two optical networks. The broadband market has driven network operators to consider merger of networks. This thesis therefore looks at the resource optimization of the merger of two separate networks but in the same geographical locations. Network planners can have a greater appreciation in fully utilizing existing resources through interconnection links and reduced number of operational fiber links.

Chapter 3

The Analysis Model

In this Chapter, a minimum cost model is developed for two co-existing networks to find the optimal interconnection nodes and fiber links to be saved. The model and constraints will be discussed. Mathematical programming methods are commonly used to formulate the spare capacity planning problem for link and path [2], [38], [39]. Integer linear programming model, which is polynomial-time bounded, seems to be the most suitable approach. A well-supported and developed program, CPLEX, was selected for this purpose [40].

In order to merge two co-existing networks, fiber interconnection links that connect network nodes located in the same city need to be built. The objective is to find which co-located nodes need to be interconnected to provide maximum cost savings for the merged network, and then derive which fiber links can be saved after such a merger.

A preliminary model was first presented in [2] to explore a dual-ring 8-location network of real deployments in China. It focuses on the study of the number of interconnection links in relation to the number of *commodities* (the traffic between different nodes). Further studies were conducted in [39] which provides a more comprehensive study of the number and the location of interconnection links, the critical interconnection build cost (CIBC), and the optimal fiber saving under the dual-ring topology as well as other topologies with various interconnection build cost.

The standard multi-commodity formulation for the Minimum Cost Capacity Installation (MCCI) problem has been commonly used in the design of telecommunication and distribution networks [38], [41]. Different algorithms have been developed for network programming. Multi-commodity network flow problem has been developed in traffic engineering [42]. Many references are available in this area. The model in the thesis is designed with reference to these materials. It will optimize the network consolidation to arrive at its optimal cost and derive the corresponding interconnection nodes with locations. Standard mixed integer multi-commodity formulation can integrate topology planning, capacity selection, survivability and the Open Shortest Path First (OSPF) routing protocol together all in one model [43]. Therefore, it is best suited for our objective. Integer programming approach is often used for space capacity planning problem for link and path. Linear programming (LP) model that is polynomial-time bounded and rounds the solution to integer values seem to be the best approach and logical model for the research [44].

When mathematical models are linear and continuous, simplex method can be used. When model comprises of linear and discrete variables, then branch-and-bound (B&B) method and branch and cut (B&C) method are the most common optimization techniques. Commercial solver CPLEX program builds in with all three of these methods [21]. Details of the above methods can be found in [45], [46].

Optimization is a math-based technology that can allocate resources for maximum operational efficiency. CPLEX is one of the world's leading mathematical programming optimizers. ILOG CPLEX has solved problems with millions of constraints and variables. It has a robust algorithm for demanding problems. ILOG CPLEX mixed integer optimizer can solve quadratic terms in the objective function and/or constraints. It contains sophisticated mixed integer preprocessing routines and implements default strategies. Users can customize the cutting plane and heuristics strategies based on users' knowledge and experience. This optimizer can improve utilization for resources and at the best possible time. It will explore alternatives in minutes [47]. With the aforementioned features, CPLEX program is therefore chosen as the mathematical tool for the case studies.

3.1 Objective function and basic assumptions

Our objective is to determine the minimum cost for the overall merged network. Flow, fiber and node cost determine the ultimate optimal cost for the network. Some basic assumptions include all links are uni-directional, only existing networks are being analyzed, and additional links are not allowed for intercity. Optimal cost and interconnection links at co-located nodes are being investigated. The following objective function is presented which is commonly used for node-arc formulation. The objective function is to minimize the overall cost C:

$$C = \sum_{1 \le k \le K} \sum_{(i,j) \in A} c_{ij}^k x_{ij}^k + \sum_{(i,j) \in A} f_{ij} y_{ij} + \sum_{i \in V} e_i z_i \quad (1)$$

In this formulation, $G = (V, A)$ is the directed network. V is a set of N vertices or nodes. A is a set of $N \times N$ links. k is the commodity index with value from 1 to K, whereas K is the total number of commodities. The objective is to minimize the total cost C by reducing the number of fiber links required. x_{ij}^k is the flow indicator of commodity k on link (i,j). Link (i,j) refers to the link from node i to node j. c_{ij}^k is the cost per unit flow of commodity k on link (i,j). f_{ij} of link (i,j) is the building and operation cost of fiber link from node i to node j where $1 \le i \le N$ and $1 \le j \le N$. This includes both the cost of the existing operational fiber links (OFL), i.e. fiber operating cost, and the interconnection links (IC) to be built, i.e. interconnection operating cost and interconnection build cost (IBC). y_{ij} is a binary variable indicating whether link (i,j) is available in the network. e_i is the fixed cost and operating cost of the equipment in node i. z_i is a binary variable indicating whether the network contains node i or not.

This objective function takes into account the traffic flow, the fiber links, and the node cost independently. All these important factors together determine the optimal cost of the infrastructure for the operator.

3.2 Constraints

Various constraints are created in order for the objective function to be more adapted to the real situations.

The constraints are given in the following.

$$\sum_{(i,j)\in A} x_{ij}^{k} - \sum_{(i,j)\in A} x_{ji}^{k}$$

$$= \begin{cases} v^k & \text{if } i = s^k \\ -v^k & \text{if } i = d^k \\ 0 & \text{otherwise} \end{cases} \qquad \forall i,j \in V,\ 1 \le k \le K \quad (2)$$

Eq. (2) is the flow constraint for commodity *k*. v^k is the volume of commodity *k*. s^k is the source of commodity *k*, where $1 \le k \le K$. d^k is the destination of commodity *k*. Commodity is the traffic flow from an origin node to a destination node. The flow that comes in to a node is equal to that goes out and can not be larger than the volume of commodity *k* [2], [38], [41]. No loss will occur at the node location.

$$\sum_{1\le k\le K} x_{ij}^{k} \le u_{ij} y_{ij} \qquad \forall (i,j) \in A \qquad (3)$$

Eq. (3) ensures that the overall flow on each link cannot exceed the capacity of the fiber link. u_{ij} is the capacity of fiber link (*i,j*) [41]. The capacity of fiber link dictates the maximum capacity of the flow on a specific link.

$$\sum_{(i,j)\in A} (x_{ij}^{k} + x_{ji}^{k}) \le q_i z_i \qquad \forall i \in V, 1 \le k \le K \qquad (4)$$

Eq. (4) states that the total flow cannot exceed the capacity of the equipment of node i. q_i is the capacity of equipment of node i. Once it exceeds this limit, flow will not be able to flow through the node.

$$x_{ij}^{k} \geq 0 \qquad \forall (i,j) \in A, 1 \leq k \leq K \qquad (5)$$

Eq. (5) states that flow is non-negative. If there is no flow then no flow cost will incur.

$$y_{ij} \leq a_{ij} \qquad \forall (i,j) \in A \qquad (6)$$

Eq. (6) tells which fiber links are allowed to be used. a_{ij} is a binary parameter indicating whether link (i,j) is allowed to be included in the network. No new installation of fiber links is allowed except in between the allowable interconnecting nodes i.e. co-located nodes. Our analysis is based on two existing networks and is trying to maximize the usage of existing fiber links. It is possible that installing fiber links between nodes (other than co-located nodes) are a cheaper alternative than using existing fiber links. However, this alternative is not allowed in our analysis.

$$y_{ij} = \{0,1\} \qquad \forall (i,j) \in A \qquad (7)$$

$$z_i = \{0,1\} \qquad \forall i \in V \qquad (8)$$

Eq. (7) and (8) define y and z to be binary variables [2]. y_{ij} and z_i is operational when they are set to 1.

The objective of the model is to find the optimal cost when merging two co-existing networks. The intention is to maximize the use of existing networks without adding additional fiber links except for the purpose of interconnection at co-located nodes. This model enables us to find the optimal interconnection locations and the fiber links to be saved.

3.3 Specific assumption

The topological features of the fiber links play a fundamental role in determining the key performance indices of a network. They influence optical signal quality, optical spectral efficiency, potential connectivity, maximum throughput, and survivability [48]. Therefore various topologies are explored and compared.

3.3.1 Dual-ring topology used

This thesis will begin with a network, which is part of a real China network with dual-ring topology as shown in Fig. 3.1 and then onto the circle, tree, mesh, and bus topologies. The dual-ring networks consist of two co-located rings that link eight cities. All cites have node-degree of four except Wuhan.

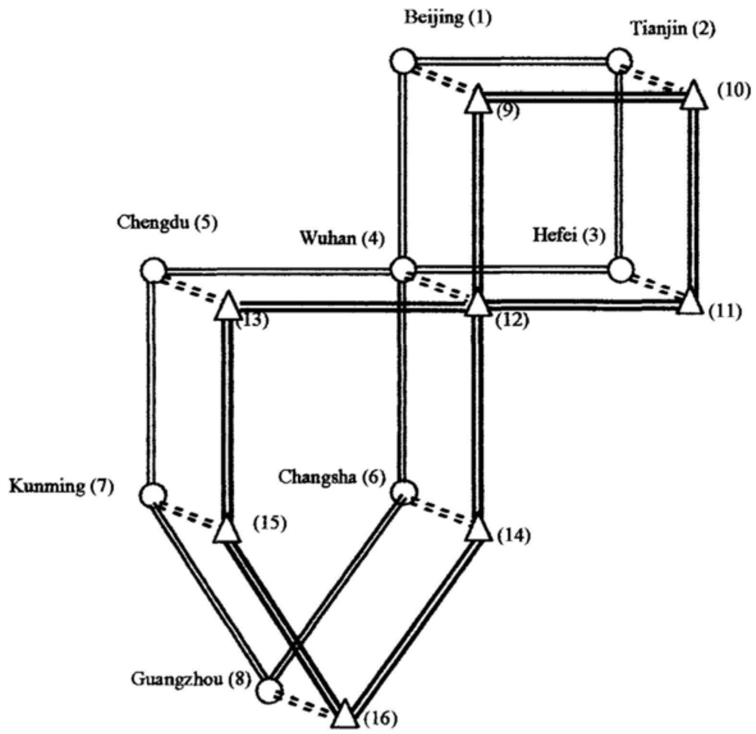

Figure 3.1 Two dual-ring-topology networks with 16 nodes / 36 links

○& △: nodes on network A & B.

══════ : two unidirectional links

======= : interconnection links

3.3.2 Specific assumptions for the Dual-Ring Topology

In Figure 3.1 model, some specific assumptions are made. Two networks with identical geographic coverage are considered. There are 16 nodes in total, with eight nodes in each network. Each fiber supports unidirectional traffic. Two fiber links are used between nodes before merging. Assume that no losses in both nodes and fiber links will occur when commodities flow within the network [2], all incoming and through traffic will go through nodes with no losses. The distances of all co-located nodes are assumed to be the same. For instance the distances from node 1 to node 9, node 2 to node 10 ..., and node 8 to node 16 in Fig. 3.1 are the same, thus all interconnection build costs are assumed to be the same. In practice, the distance between the co-located nodes of different cities may vary.

All interconnection links can only occur at the co-located nodes. For example, in Fig. 3.1, Beijing is node 1 and node 9 in network A and B, respectively, and interconnection link is permissible between node 1 and node 9. Connection between node 1 to node 3 or node 11 is not permissible. Only existing fiber links can be operational (no new installation of fiber between nodes in different locations is allowed) other than interconnection links (i.e. within two co-located nodes). Traffic demands vary, depending on user behavior, performance of network elements, and routing policies [25], [49]. However, traffic flow is assumed to be running within all nodes in the two existing networks and runs from each node to every other node (full connectivity between any two nodes in the merged network) [50]. Therefore a total of 240 (=16 nodes $\times$15) traffic commodities are used, each is assumed with a uniform capacity of 0.6.

Flow cost is assumed to be negligible as the cost for packet transmission has been considered under fiber operation cost and node operation cost. The flow cost is assumed uniform with a minimal value of 1. Fiber links operating cost, if the fiber is used, is assumed to be uniform with a value of 1000. Interconnection fiber operating cost of 100 is assumed. In practice, fiber links vary in length therefore fiber operating cost also varies. In the case studies, the fiber operation cost is assumed to be constant to study the effect of different topologies. Existing fiber build cost is assumed to be zero in our case analysis. In practice, unused fiber links may be sold to recover some CAPEX in order to lower the overall cost of the network. That can be explored in the future work to allow negative flow cost in case the link is not used. On the other hand, the acquisition cost of the existing fiber will also need to be taken into account.

Node operating cost is also assumed to be uniform at a value of 100. The issue of node degree and connectivity will be considered in Chapter 6. But in reality, it will vary depending upon the equipment installed at the node site. Fiber capacity u_{ij} and equipment capacity q_i are not considered with limitations in our analysis, therefore are set at a relatively large value of 1000. Both fiber and equipment capacity are not of concern since equipment can be relocated from redundant nodes and therefore poses no limitation to capacity. There are restrictions on the usage of certain fiber links a_{ij}, depending on the network topology; therefore it needs to be defined. Only existing fiber links and newly constructed interconnection links can be operational in order to maximize the usage of existing fiber links. Since the model intends to merge two existing networks, no build cost for existing fiber links is assumed. However, the build costs of the interconnection links are varied in this study.

Most of the parameters have been kept constant, except for interconnection build cost, in order to see the effect on fiber links saved and the number of interconnection links used for the merged network. These parameters are summarized in Table 3.1 for reference.

Parameters	Value
Number of Commodities	240
Flow Cost	1
Fiber Operation Cost	1000
Interconnection Fiber Operation Cost	100
Fiber Build Cost for Existing Fiber Links	0
Node Operation Cost	100
Fiber Capacity	1000
Equipment Capacity	1000
Size of Commodities	0.6
Interconnection Fiber build cost	1 to 20000

Table 3.1 Parameters for the merger of two networks & their values

It is necessary to examine different topologies, since routing configuration and backbone topology have significant implications on user performance and resource efficiency [25]. The result of the dual-ring topology will be compared with that of various topologies in order to have an appreciation of the effect of fiber links saved.

3.3.3 Other topologies

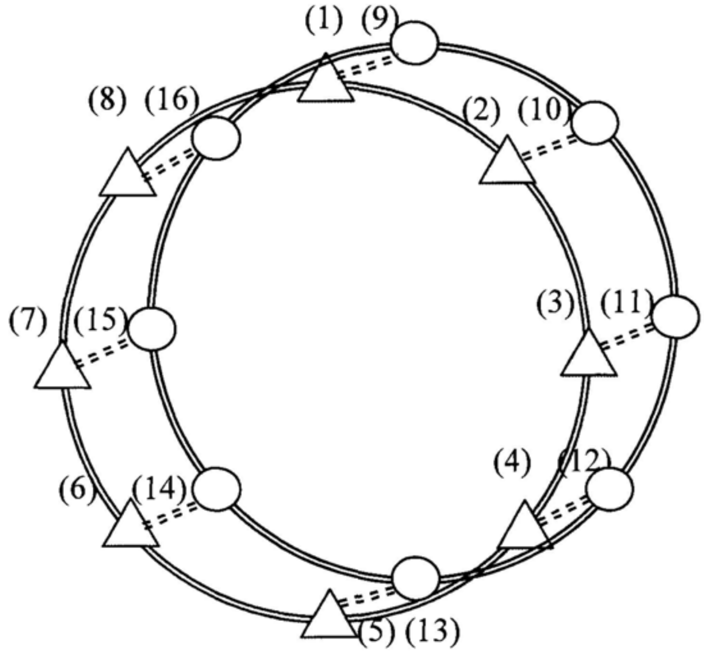

Figure 3.2 Two circle-topology networks with 16 nodes / 32 links

○& △: nodes on network A & B.

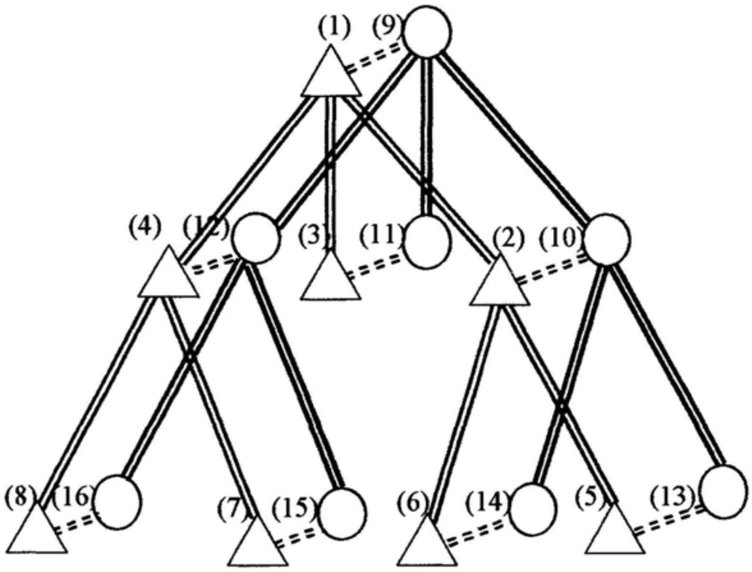

Figure 3.3 Two tree-topology networks with 16 nodes / 28 links

○& △: nodes on network A & B.

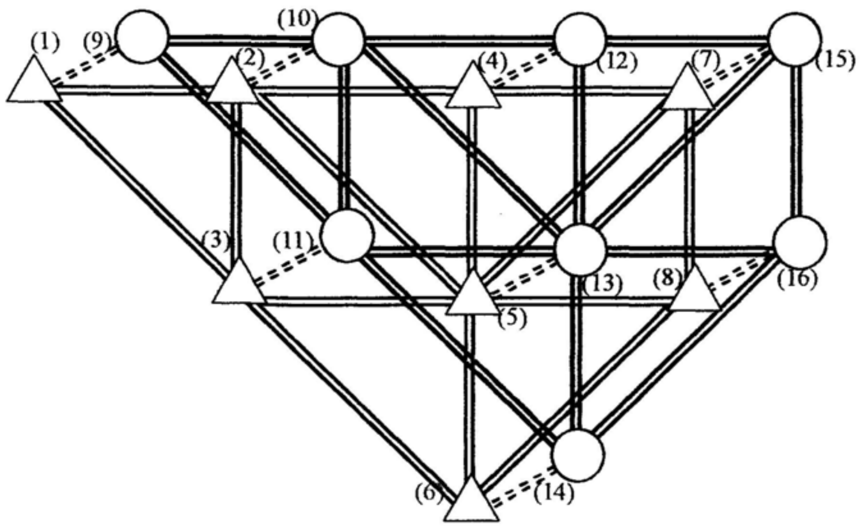

Figure 3.4 Two mesh-topology networks with 16 nodes / 56 links

○& △: nodes on network A & B.

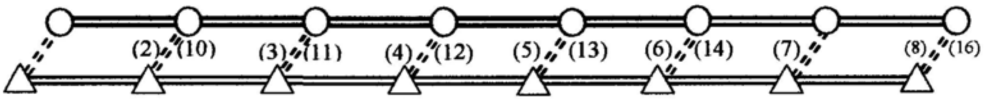

Figure 3.5 Two bus-topology networks with 16 nodes / 28 links

○& △: nodes on network A & B.

Topologies are generally divided into regular and irregular categories. Regular topologies follow a well-defined function between nodes. They are generally symmetrical and have strong connectivity. Tree, circle, mesh topologies are considered to be regular topology e.g. tree and bus topology requires a minimum number of N-1 links to connect N nodes [51].

3.3.4 Specific assumptions for other topologies

Four other topologies are used in the investigation, namely circle, tree, mesh, and bus as shown in Fig. 3.2 to 3.5. There are two types of fiber links, the operational (OFL) (for intercity) and the interconnection (IC) (for co-located nodes within one city).

For the sake of clarity, the illustrations use double-line for the two fiber links of opposite directions. Interconnection links will only occur, if needed, in co-located nodes. The optimal location and the number of interconnection links will vary, depending upon the network topology and interconnection build cost. Our objective is to find the fiber links that can be saved and the optimal interconnection locations.

All of the five topologies are investigated and compared. In Fig. 3.1, the dual-ring topology actually is a reduced form of the real fiber network in China in [2]. Fig. 3.2 to 3.5 are typical topologies for consideration. The number of nodes are fixed to eight per network for all topologies to facilitate fair comparison amongst these topologies with different number of fiber links. The merger of two mesh networks is expected to result in the most fiber link savings. It has more alternative routes for the traffic to choose from and therefore it is easier to find redundant fiber links that can be removed. Since the mesh topology has the most number of fiber links compared with other topologies, more saving in fiber links is possible after merging. It is of interest to find out how many fiber links can be saved and the locations of interconnection links for different topologies.

Similar parameters as in Table 3.1 are used for the other topologies. Dual-ring topology can then be compared with these topologies. Interconnection build cost has a certain effect upon the percentage of total fiber operating cost saved, and the number of interconnection fiber links. These shall be discussed in Chapter 5.

Chapter 4

Analysis results

CPLEX program is applied to the above model. Various results are analyzed to see the number and location of interconnection links and the optimal cost for particular networks under the merger condition.

4.1 Part of a real China dual-ring network

This thesis will firstly investigate a dual-ring network that is part of a real China network (Fig. 3.1) then onto other topologies. The China network was used to test the application of the model. Table 4.1 shows the effect of interconnection build cost (IBC) to the optimal cost, the required number of fiber links, and the total operating cost of fiber links before and after merging, for the dual-ring topology (Fig. 3.1). IBC is chosen as a variable in the study as the interconnection links are the new links to be installed and optimized. The total IBC is directly related to the number and location of interconnection links to be built for merging the two networks. IBC per link is varied from 1 to 20,000.

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	12161	36	9	36000	9000	27000	8	808	26192	72.75%

2	400	14986	36	9	36000	9000	27000	8	4000	23000	63.89%
3	600	16561	36	9	36000	9000	27000	8	5600	21400	59.44%
4	800	17706	36	12	36000	12000	24000	4	3600	20400	56.67%
5	900	18238	36	14	36000	14000	22000	2	2000	20000	55.55%
6	1000	18875	36	14	36000	14000	22000	2	2200	19800	55%
7	2000	20952	36	14	36000	14000	22000	2	4200	17800	49.44%
8	4000	24503	36	14	36000	14000	22000	2	8200	13800	38.33%
9	6000	28952	36	14	36000	14000	22000	2	12200	10000	27.78%
10	8000	32952	36	14	36000	14000	22000	2	16200	5800	16.11%
11	10000	36952	36	14	36000	14000	22000	2	20200	1800	5.00%
12	20000	41958	36	14	36000	14000	22000	2	40200	No Saving	

Table 4.1 Optimal Cost vs. Interconnection Build Cost (IBC)

for dual-ring topology.

OFL: Operational Fiber Link; IC: Interconnection Link

As the interconnection build cost increases, the optimal cost increases. When IBC is low, more interconnection links can be used, the number of required operational fiber links (OFL) reduces substantially after the merging. Total fiber operating cost, therefore, reduces significantly. However, as the interconnection build cost increases, the number of interconnection links reduces and the number of operational fiber links required increases as shown in Fig. 4.1. Fiber operating cost saved minus the build cost and operating cost of interconnection links gives the net cost saving (column (j) in Table 4.1). The percentage of the cost saved with respect to the total fiber link operating cost can then be calculated (column (k) in Table 4.1), which is also shown pictorially in Fig. 4.2. Saving of fiber link operating cost can be as high as 73% for dual-ring topology with IBC=1, representing the case that IBC is negligible. It is noted that with IBC=l, the number of operational fiber links reduces from the original 36 to 9 after merger, which will be shown later to be the minimal number. This substantial reduction in operational fiber links results in cost savings to the operator.

Table 4.2 shows the corresponding operating fiber links required, the interconnection links and the corresponding interconnection build cost for the two 8-node identical dual-ring topology networks after merging. The number of fiber links is reduced from the original 36 links to 9 links for Case 1 and to 15 links for Case 12. Interconnection links are reduced from 8 in Case 1 to 2 in Case 5.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	2/1, 4/3, 9/12, 11/10, 6/4, 4/5, 16/4, 7/8, 13/15	9	1/9, 10/2, 3/11, 12/4, 14/6,8/16,15/7, 5/13	8	8
2	400	4/1, 2/3, 9/10, 11/12, 13/12, 12/14, 6/8, 16/15, 7/5	9	1/9, 10/2, 3/11, 12/4, 14/6,8/16,15/7, 5/13	8	3200
3	600	4/1, 2/3, 9/10, 11/12, 12/13, 14/12, 8/6, 15/16, 5/7	9	1/9, 10/2, 3/11, 12/4, 6/14,16/8,7/15, 13/5	8	4800
4	800	1/2, 3/4, 12/9, 10/11, 4/5, 13/12, 8/6, 14/16, 7/8, 16/15, 5/7,15/13	12	9/1, 2/10, 11/3, 6/14	4	3200
5	900	1/2, 2/3, 3/4, 10/9, 11/10, 12/11, 4/6, 14/12, 8/6, 16/14, 8/7, 15/16, 7/5,13/15	14	9/1, 5/13	2	1800
6	1000	1/4, 2/1, 3/2, 9/10, 12/9, 10/11, 4/6, 14/12, 6/8, 16/14, 8/7, 15/16, 7/5, 13/15,	14	11/3, 5/13	2	2000
7	2000	1/2, 2/3, 3/4, 10/9, 11/10, 12/11, 4/6, 14/12, 6/8, 16/14, 8/7, 15/16, 7/5, 13/15	14	9/1, 5/13	2	4000
8	4000	1/2, 2/3, 3/4, 10/9, 11/10, 12/11, 4/6, 14/12, 6/8, 16/14, 8/7, 15/16, 7/5, 13/15	14	9/1, 5/13	2	8000

9	6000	1/4, 2/1, 3/2, 9/10, 12/9, 10/11, 4/6, 14/12, 6/8, 16/14, 8/7, 15/16, 7/5, 13/15	14	11/3, 5/13	2	12000
10	8000	1/2, 2/3,3/4, 10/9, 11/10, 12/11, 4/6, 14/12, 6/8, 16/14, 8/7, 15/16, 7/5 13/15,	14	9/1, 5/13	2	16000
11	10000	2/1, 3/2, 4/3, 9/10, 10/11, 11/12, 6/4, 12/14, 8/6, 14/16, 7/8, 16/15, 5/7, 15/13	14	1/9, 13/5	2	20000
12	20000	4/1,1/2, 2/3, 10/9, 9/12, 11/10, 5/4, 12/13, 6/8, 16/14, 8/7, 15/16, 7/5, 13/15	14	3/11, 14/6	2	40000

Table 4.2 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for dual-ring topology

Table 4.2 also shows the number of interconnection links needed for different IBC. The interconnection locations can be determined and the extra cost required for the merged network (the total IBC) can then be calculated. The number of interconnection links reduces as IBC increases. It eventually reduces to two interconnection links with one going from network A to network B and the other in the reverse direction. With the cost saving from Table 4.2 on fiber links saved and the extra cost for interconnection links, the net cost saving for a merged network can then be calculated as shown in Table 4.1. When the saving in operating cost of fiber link is not able to cover high interconnection build cost, merged network will not result in cost saving e.g. in Case 12.

Further discussion will be carried out in Chapter 5 of the thesis. These results have already shown that merger of two networks will result in savings to the operator.

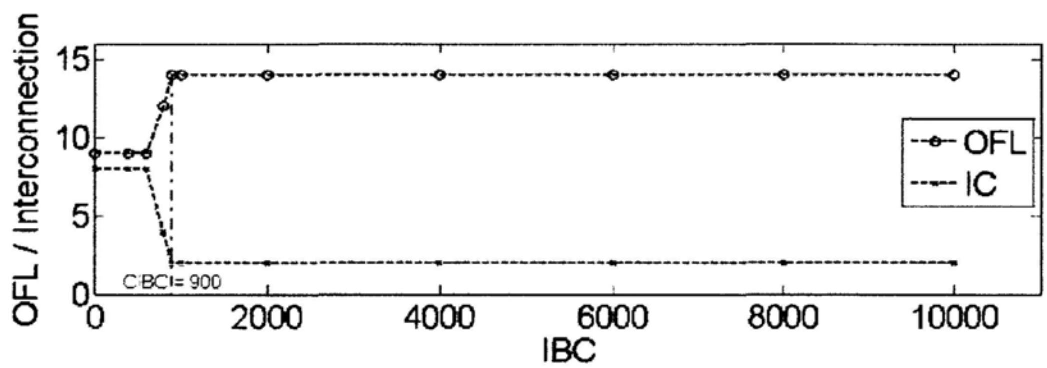

Figure 4.1 Number of Operational Fiber Link (OFL) and Interconnection Link (IC)

vs. Interconnection Build Cost (IBC) for dual-ring topology

CIBC: Critical IC build cost (when number of IC becomes 2)

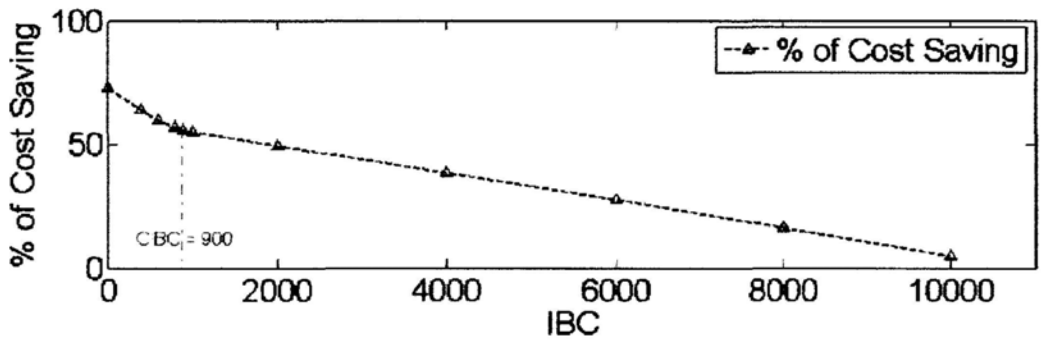

Figure 4.2 Percentage of cost saving vs. Interconnection Build Cost (IBC) for dual-ring topology

4.2 Results for other topologies

Similar tables as Table 4.1 and 4.2 have been derived for all the topologies given in Fig. 3.2 to 3.5. Table 4.3 & 4.4 show the results for the circle topology in Fig. 3.2. Table 4.5 and 4.6 show the results for the tree topology as shown in Fig. 3.3. Table 4.7 and 4.8 show the results for the mesh topology in Fig 3.4. Table 4.9 and 4.10 show the results for the bus topology in Fig. 3.5. Summary Table 4.11 and 4.12 are also given for easy comparison. In Table 4.11, additional IBC values are considered in the case studies to capture the effect of the reduction in the number of interconnection links as indicated by the values in parentheses. Fig, 4.3 provides % of cost saving vs. IBC for all five topologies. Fig. 4.4 and 4.5 shows the number of OFL and IC vs. IBC. In Table 4.12, the optimal cost vs. IBC for the various topologies is given. These various effects and their implications will be discussed in Chapter 5.

Circle topology

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	11554	32	8	32000	8000	24000	8	808	23192	72.475%
2	400	14446	32	8	32000	8000	24000	8	4000	20000	62.50%

3	800	17839	32	8	32000	8000	24000	8	7200	16800	52.50%
4	900	18281	32	14	32000	14000	18000	2	2000	16000	50%
5	1000	18577	32	14	32000	14000	18000	2	2200	15800	49.375%
6	2000	20939	32	14	32000	14000	18000	2	4200	13800	43.125%
7	4000	24938	32	14	32000	14000	18000	2	8200	9800	30.625%
8	6000	28939	32	14	32000	14000	18000	2	12200	5800	18.125%
9	8000	32939	32	14	32000	14000	18000	2	16200	1800	5.625%
10	20000	56940	32	14	32000	14000	18000	2	40200	No Saving	--

Table 4.3 Optimal Cost vs. Interconnection Build Cost (IBC) for circle topology.

OFL: Operational Fiber Link; IC: Interconnection Link

In Table 4.3, the circle topology requires a minimum of 16 fiber links including operational fiber links and interconnection links in all cases. Optimal cost is shown here. The Operational fiber links (OFL) before merger and after merger are indicated. Number of interconnection fiber links (IC) is shown. Respective cost saving is highlighted for the various IBC. Further discussion will be given in next Chapter.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	2/3, 4/5, 6/7, 8/1, 9/10, 11/12, 13/14, 15/16	8	1/9, 10/2, 3/11, 12/4, 5/13, 14/6, 7/15, 16/8	8	8
2	400	1/2,3/4, 5/6, 7/8, 10/11, 12/13, 14/15, 16/9	8	9/1, 2/10, 11/3, 4/12, 13/5, 6/14, 15/7, 8/16	8	3200
3	800	1/2,3/4, 5/6, 7/8, 10/11, 12/13, 14/15, 16/9	8	9/1, 2/10, 11/3, 4/12, 13/5, 6/14,15/7, 8/16	8	6400
4	900	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	1800

5	1000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	2000
6	2000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	4000
7	4000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	8000
8	6000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	12000
9	8000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	16000
10	20000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	40000

Table 4.4 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for Circle Topology

In Table 4.4, the operational fiber links and the interconnection links are shown for the circle topology. Locations of the OFL and IC are shown. The total IBC cost is also calculated.

Tree topology

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	16821	28	14	28000	14000	14000	6	606	13394	47.83%

2	400	18860	28	14	28000	14000	14000	5	2500	11500	41.07%
3	800	20860	28	14	28000	14000	14000	5	4500	9500	33.93%
4	1000	21860	28	14	28000	14000	14000	5	5500	8500	30.35%
5	1500	24360	28	14	28000	14000	14000	5	8000	6000	21.43%
6	1800	25860	28	14	28000	14000	14000	5	9500	4500	16.67%
7	2000	26580	28	20	28000	20000	8000	2	4200	3800	13.57%
8	4000	30580	28	20	28000	20000	8000	2	8200	No Saving	--

Table 4.5 Optimal Cost vs. Interconnection Build Cost (IBC) for tree topology.

In Table 4.5, the optimal cost for the tree topology is generally higher than that of the circle topology. Less than 48% of fiber cost savings occurs for this topology with respect to the various IBC. More operational fiber links are required for the tree topology. Relatively speaking tree topology is a less efficient topology. In Case 1, the IC result is 6. Other results (Case 2 to Case 6) show that the IC is 5. This is because the saving in flow cost will outweigh the build and operating cost of the extra IC; since the extra IC only costs 101 when IBC=1.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	1/2, 2/5, 2/6, 1/3, 4/1, 7/4, 8/4, 10/9, 13/10, 14/10, 11/9, 9/12, 12/15, 12/16	14	9/1, 3/11, 5/13, 6/14, 15/7, 16/8	6	6
2	400	1/2, 2/5, 2/6, 3/1, 4/1, 7/4, 8/4, 10/9, 13/10, 14/10, 9/11, 9/12, 12/15, 12/16	14	11/3, 5/13, 6/14, 15/7, 16/8	5	2000
3	800	1/2, 2/5, 2/6, 3/1, 4/1, 7/4, 8/4, 10/9, 13/10, 14/10, 9/11, 9/12, 12/15, 12/16	14	11/3, 5/13, 6/14, 15/7, 16/8	5	4000
4	1000	1/2, 2/5, 2/6, 3/1, 4/1, 7/4, 8/4, 10/9, 13/10, 14/10, 9/11, 9/12, 12/15, 12/16	14	11/3, 5/13, 6/14, 15/7, 16/8	5	5000

5	1500	1/2, 2/5, 2/6, 3/1, 4/1, 7/4, 8/4, 10/9, 13/10, 14/10, 9/11, 9/12, 12/15, 12/16	14	11/3, 5/13, 6/14, 15/7, 16/8	5	7500
6	1800	1/2, 2/5, 2/6, 3/1, 4/1, 7/4, 8/4, 10/9, 13/10, 14/10, 9/11, 9/12, 12/15, 12/16	14	11/3, 5/13, 6/14, 15/7, 16/8	5	9000
7	2000	1/2, 2/5, 2/6, 6/2, 1/3, 3/1, 4/1, 7/4, 4/8, 8/4, 10/9, 13/10, 10/14, 14/10, 9/11, 11/9, 9/12, 12/15, 12/16, 16/12	20	5/13, 15/7	2	4000
8	4000	1/2, 2/5, 5/2, 2/6, 1/3, 3/1, 4/1, 7/4, 4/8, 8/4, 10/9, 10/13, 13/10, 14/10, 9/11, 11/9, 9/12, 12/15, 12/16, 16/12	20	6/14, 15/7	2	8000

Table 4.6 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for tree topology.

In Table 4.6, both OFL and IC locations are shown. All IC locations are located at the leaves of the tree topology. It acts as an intermediate node in any communication between nodes in the two halves of the tree [51].

Mesh Topolgy

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	10634	56	8	56000	8000	48000	10	1010	46990	83.91%
2	400	14543	56	9	56000	8000	47000	8	4000	43000	76.78%

3	800	17145	56	10	56000	10000	46000	6	5400	40600	72.50%
4	1000	17940	56	13	56000	13000	43000	3	3300	39700	70.89%
5	1500	18941	56	14	56000	14000	42000	2	3200	38800	69.28%
6	2000	20706	56	14	56000	14000	42000	2	4200	37800	67.50%
7	4000	23950	56	14	56000	14000	42000	2	8200	33800	60.36%

Table 4.7 Optimal Cost vs. Interconnection Build Cost (IBC)

for mesh topology.

OFL: Operational Fiber Link; IC: Interconnection Link

In Table 4.7, mesh topology has a substantial fiber cost saving because this topology has the most number of fiber links and has more alternative routes for traffic to route. It is the most efficient topology. The case analysis results have some minor variation in the number of operational fiber links and interconnection links compared with the analytical results in Sec. 5.2. It is because the mesh topology has a much larger tree size in the case studies. The analysis results generally agree well with the analytical results with some minor deviation due to simulation uncertainty.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	1/3, 4/2, 8/7, 10/9, 11/14, 13/12,15/13, 14/16	8	9/1, 2/10, 3/11, 12/4, 5/13, 13/5, 6/14, 14/6, 7/15, 16/8	10	10
2	400	1/2, 5/3,4/7, 6/8,10/12, 11/9, 11/14, 15/13,16/13	9	9/1, 2/10, 3/11,12/4, 13/5, 14/6, 7/15, 8/16	8	3200
3	800	3/1, 5/2, 6/3, 4/7, 8/6, 9/11, 10/12, 11/14, 14/13, 15/16	10	1/9, 2/10, 12/4, 13/5, 7/15, 16/8	6	4800

4	1000	3/1, 2/3, 4/2, 7/4, 6/5, 5/7, 8/6, 9/10, 10/12, 13/11, 11/14, 12/15, 15/13	13	1/9, 14/6, 16/8	3	3000
5	1500	3/1, 2/3, 4/2, 7/4, 6/5, 5/8, 8/7, 9/10, 10/12, 13/11, 11/14, 12/15, 16/13, 15/16	14	1/9, 14/6	2	3000
6	2000	2/1, 1/3, 4/2, 3/6, 7/4, 8/5, 6/8, 9/10, 11/9, 10/12, 14/11, 12/15, 13/16, 16/14	14	5/13, 15/7	2	4000
7	4000	2/1, 1/3, 4/2, 3/5, 7/4, 6/8, 8/7, 10/9, 9/11, 12/10, 11/14, 15/12, 13/16, 16/15	14	5/13, 14/6	2	8000

Table 4.8 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for mesh topology

In Table 4.8, both OFL and IC locations are shown for mesh topology. In Case 3, an analytical result shows that there shall be 8 OFL and 8 IC, which equates operating cost to 40800 = (48 OFL saved × OFL operating cost of 1000) – 8 IC × (IBC of 800 + IC operating cost of 100); not taken into account of flow cost. Analysis result arrives at 10 OFL and 6 IC, which provide fewer saving of 200 to the operator i.e. 40600. Flow cost saving will again justify for flow to route through 10 OFL and 6 IC in lieu of 8 OFL and 8 IC, therefore the analysis result is reasonable. However, the minimum fiber links required for OFL and IC remains to be 16. Similarly for Case 4, it will be shown analytically in Sec. 5.2.3 that there shall be 14 OFL and 2 IC. The analysis result is 13 OFL and 3 IC. It is more viable to have an extra IC that costs 1100 vs. the savings of one OFL i.e. 1000 + flow cost. The analysis results are in line with the analytical results.

Bus topology

Case	IBC	Optimal Cost	No. of OFL Required: Before Merging	No. of OFL Required: After Merging	Operating Cost of OFL: Before Merging	Operating Cost of OFL: After Merging	OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	168156	28	14	28000	140000	14000	3	303	13697	48.92%
2	200	17338	28	14	28000	140000	14000	2	600	13400	47.86%
3	400	17739	28	14	28000	140000	14000	2	1000	13000	46.43%
4	600	18139	28	14	28000	140000	14000	2	1400	12600	45.00%
5	800	18539	28	14	28000	140000	14000	2	1800	12200	43.57%
6	1000	18939	28	14	28000	140000	14000	2	2200	11800	42.14%
7	2000	20939	28	14	28000	140000	14000	2	4200	9800	35.00%
8	4000	24929	28	14	28000	140000	14000	2	8200	5800	20.71%
9	6000	28938	28	14	28000	140000	14000	2	12200	1800	6.43%
10	10000	36937	28	14	28000	140000	14000	2	20200	No Saving	--

Table 4.9 Optimal Cost vs. Interconnection Build Cost (IBC) for bus topology.

OFL: Operational Fiber Link; IC: Interconnection Link

Table 4.9 shows the results for the bus topology. This topology has less than 50% fiber links savings and it is again not an efficient topology.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	2/1, 3/2, 4/3, 5/4, 5/6, 6/7, 7/8, 9/10, 10/11, 11/12, 12/13, 14/13, 15/14, 16/15	14	1/9, 8/16,13/5	3	3
2	200	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	400
3	400	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	800
4	600	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	1200
5	800	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	1600
6	1000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	2000
7	2000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	4000
8	4000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	8000
9	6000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	12000
10	10000	2/1, 3/2, 4/3, 5/4, 6/5, 7/6, 8/7, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16	14	1/9, 16/8	2	20000

Table 4.10 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for bus topology

For the bus topology, the interconnection fiber links are located at the end nodes of the network except Case 1. This deviation is again a result of the extra IC that is more justifiable in comparison with the flow cost incurred. When IBC is 1, it is more economic to use IC than incurring extra flow cost.

4.3 Summary

With the results for the various topologies, the following summary provides a clear picture of the relationship between IBC and the various topologies. As IBC increases, % of cost saving decreases for all the five topologies. The percentage of fiber links cost saving is indicated in Table 4.11 and Fig. 4.3. The more efficient topologies have a much higher cost savings than the less efficient ones. Mesh topology achieves more cost saving than other topologies.

Interconnection Build Cost	Dual-ring %	Circle %	Tree %	Mesh %	Bus %
1	72.75 (8)	72.47 (8)	47.83 (6)	83.91 (8)	48.92 (3)
200	-	-	-	-	47.86 (2)
400	63.89 (8)	62.50 (8)	41.07 (5)	76.78 (8)	46.43 (2)
600	59.44 (8)	-	-	-	45.00 (2)
800	56.67 (4)	52.50 (8)	33.93 (5)	72.50 (6)	43.57 (2)
900	55.55 (2)	50.00 (2)	-	-	-
1000	55.00 (2)	49.38 (2)	30.35 (5)	70.89 (3)	42.14 (2)
1500	-	-	21.43 (5)	69.28 (2)	-
1800	-	-	16.67 (5)	-	-
2000	49.44 (2)	43.13 (2)	13.57 (2)	67.50 (2)	35.00 (2)
4000	38.33 (2)	30.63 (2)	Nil (2)	60.36 (2)	20.71(2)

Table 4.11 Summary of the merger of two 8-node identical networks with various topologies

Percentage of Fiber Cost Saving vs. Interconnection Build Cost (IBC)

for two 8-node identical networks with five different topologies

The number in ( ) is the number of interconnections used.

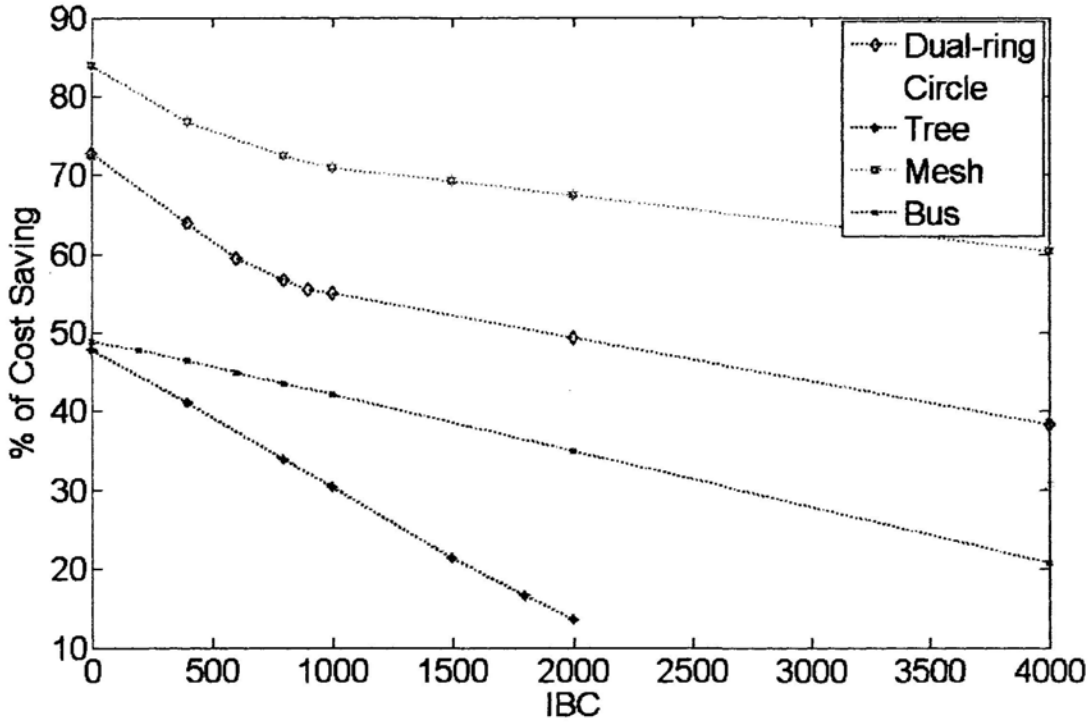

Figure 4.3 Percentage of Fiber Cost Saving vs. Interconnection Build Cost (IBC)

for two 8-node identical networks with five different topologies

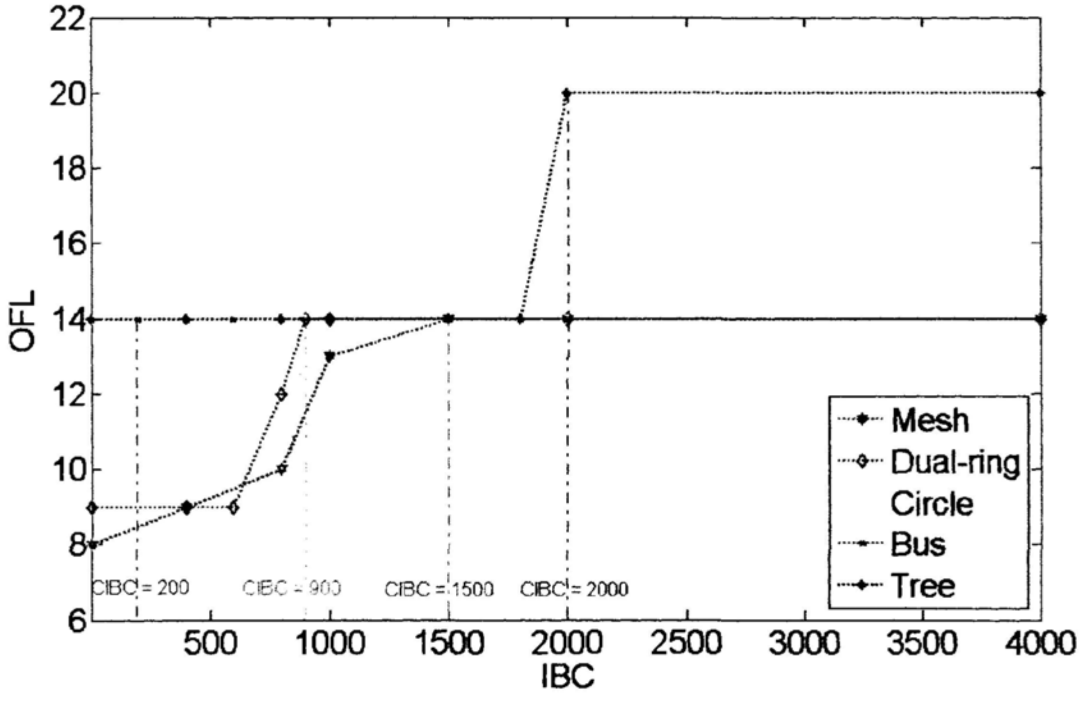

Figure 4.4 Number of Operational Fiber Links (OFL) vs. Interconnection Build Cost (IBC)

for two 8-node identical networks with five different topologies

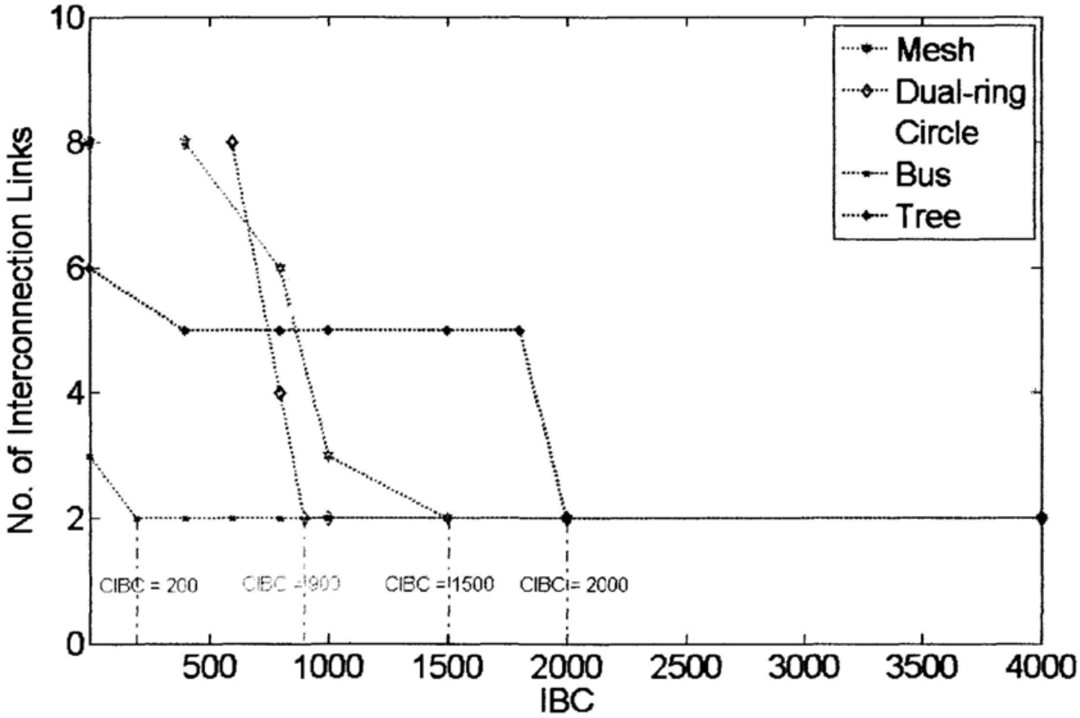

Figure 4.5 Number of Interconnection Links (IC) vs. Interconnection Build Cost (IBC)

for two 8-node identical networks with five different topologies

As IBC increases, Figure 4.4 and 4.5 show that the number of OFL increases and IC decreases. IC will become two after CIBC for all topologies. CIBC occurs at different IBC depending on the type of topology. When IBC is negligible, it is cheaper to have an additional interconnection link as seen in the bus topology in Fig. 4.5. The flow cost outweighs the additional IC cost in the merged network.

Interconnection Build Cost	Dual-ring	Circle	Tree	Mesh	Bus
1	12161	11555	16820	10634	15424
200	-	-	-	-	17338
400	14986	14446	18860	14624	17739
600	16561	-	-	-	18139
800	17706	17839	20860	17145	18539

Chapter 5

Analytical results and discussion

Analytical results and various observations are discussed in this chapter. We will discuss the dual-ring topology first then subsequently other topologies.

5.1 Dual-ring network

Case analysis is carried out under the free flow condition of the network. The free flow condition means that the case studies permits interconnection fiber links to be connected between any of the co-located nodes during the analysis. Case trials have been done for traffic to go through various interconnection locations and arrive at the minimum cost with the appropriate interconnection locations.

5.1.1 Optimal cost

In Table 4.1, it is clearly shown that as IBC increases, the number of interconnection links decreases. The percentage of savings in overall operating cost decreases at the same time. For Case 1 in Table 4.1 with IBC=1, which is regarded as negligible interconnection build cost, the number of interconnection links is eight. This corresponds to the maximum operational fiber links saved (27/36=75%). When IBC increases, it is more desirable to use less number of interconnection links. Since there are fewer interconnection links, less alternative routes are available for inter-network traffic. More operational fiber links will be needed to route the inter-network traffic. There is a trade-off between the increase of interconnection links and the corresponding saving in the operating cost of fiber links. More interconnection links will be used only when further saving in the operating cost of fiber links can offset the increased interconnection build cost. The OFL cost saved outweighs the interconnection cost in all cases except case 12 where IBC is set at an extremely high value. Once the OFL cost saved is less than the IBC cost there is no saving to the operator. It will not be justified to interconnect the networks in that situation.

5.1.2 Interconnection links (IC) and operational fiber links (OFL) required

The number of interconnection links eventually reduces to a minimum value of two at certain interconnection build cost (IBC=900), which is defined as the critical interconnection build cost (CIBC). Substantial savings only occur when IBC is smaller than CIBC as more interconnection links (4 to 8) can be employed to help reduce the number of operational fiber links. It can be shown if there is traffic originating from either network to the other network, the minimum number of interconnection links is two, one for each direction. In Table 4.1, CIBC occurs when IBC is 900. The number of OFL remains to be 14 and the number of interconnection links required remains to be two after CIBC i.e. Case 5 to 12. The minimum total number of OFL and IC is 16.

Analytical results can also be derived in the saving of fiber links when interconnection links are installed for all co-located nodes. When IBC is zero, all the co-located nodes may be installed with interconnection links. This will result in maximum flexibility for fiber link saving. An algorithm has been proposed to derive the minimum number of fiber links required for various networks in this situation [53]. An equation that can be applied to all the aforementioned network topologies to achieve maximum saving in fiber links is derived. Zero interconnection operating cost and full interconnection at all co-located nodes are assumed. We showed that

$$L_{min}=2B+|V|+\sum_{i=2}^{\infty} A_i(i-1) \qquad (9)$$

L_{min} is the minimum number of operational fiber links (OFL) required. B is the number of bridges in one network. A bridge is defined as the fiber link that, if removed, the network will disconnect to two sub-networks. $|V|$ is the number of remaining connected nodes of a network after the removal of all bridges. A_i is the number of articulation nodes with the removal of which the network will be divided to i sub-networks. We firstly examine whether there is any bridge (B) in one network. If so, we shall remove the bridges first and then examine whether there is any articulation nodes (A_i).

For example, in the case of the dual-ring topology in Fig. 3.1, there is no bridge in the network. $|V|$ is equal to the total number of nodes in a single network which is 8. Node 4 (or node 12) is the only articulation node. If the node is removed, the dual-ring network will be divided into two sub-networks. It means $\sum_{i=2}^{\infty} A_i(i-1) = A_2 = 1$, $A_3 = A_4 = \ldots = 0$; i=2; which gives $L_{min} = 2\times0+8+1(2-1) = 9$. Thus 75% savings in fiber links can be achieved when IBC equals to zero. Only one direction of fiber links on one network is preserved and all co-located nodes are equipped with bi-directional interconnections (total 16 interconnections at 8 locations). Traffic from one network to the other network will all be routed through interconnection links as shown in Fig. 5.1.

A Hamiltonian cycle can be found if with sufficient links in a network [52]. In graph theory, a Hamiltonian path is a path in an undirected graph (network) which visits each node exactly once. A Hamiltonian cycle is a cycle in an undirected graph (network) which visits each node exactly once and also returns to the starting node. There is no Hamiltonian cycle found in the dual-ring topology when IBC is zero. There shall also be no bridges and articulation nodes in the network. Therefore, when IBC is low and all interconnection links are used, the number of OFL shall equal to the number of nodes of one network as in circle and mesh topologies, i.e. $L_{min}=|V|$.

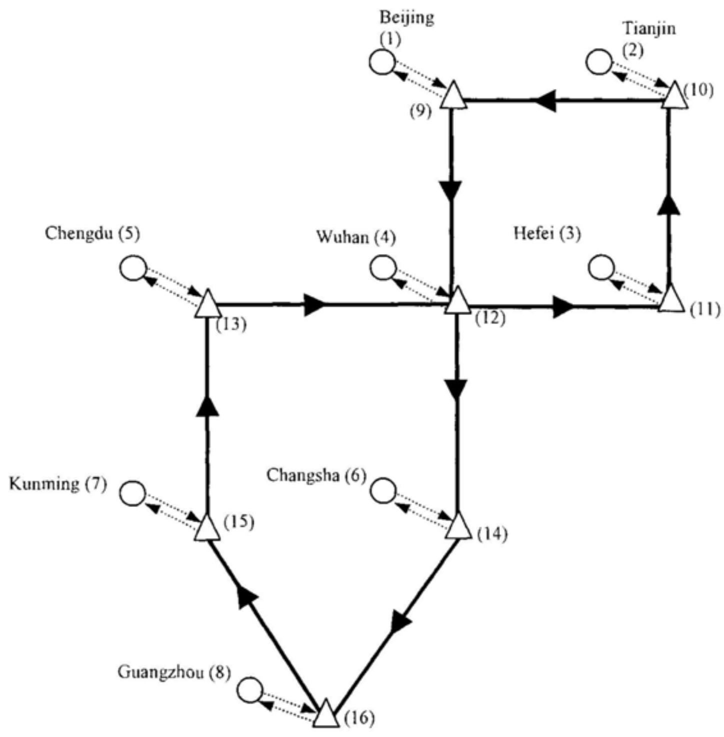

Figure 5.1 Two dual-ring topology networks after merging with IBC=0 with 16 nodes/25 links

○ & △: node on network A & B.

In terms of the number of interconnection links, this is different from case 1 in Table 4.1 (IBC=1), which has only eight interconnection links. The previous case analysis results agree with the analytical results on the number of fiber links saved. There is also a minor discrepancy in cost saving compared with the analysis results. It is because analysis results include the build cost e.g. IBC=1, and operating cost of interconnection links (=100).

5.1.3 Location of interconnection links

When the interconnection build cost exceeds CIBC, the number of interconnection becomes two (IC=2). We will investigate the locations of interconnection links. For the dual-ring topology, it is discovered that there is a Hamiltonian path that covers all the nodes in one network [52]. With two interconnection links and two Hamiltonian paths of two identical dual-ring networks, a big cycle which connects all the 16 nodes with a minimum of 7+7=14 operational fiber links (OFL) will be formed. Thus it is shown that ICs will locate at the two ends of the path which are both one hop from the articulation node (node 4 and 12). One possible solution is shown in Fig. 5.2.

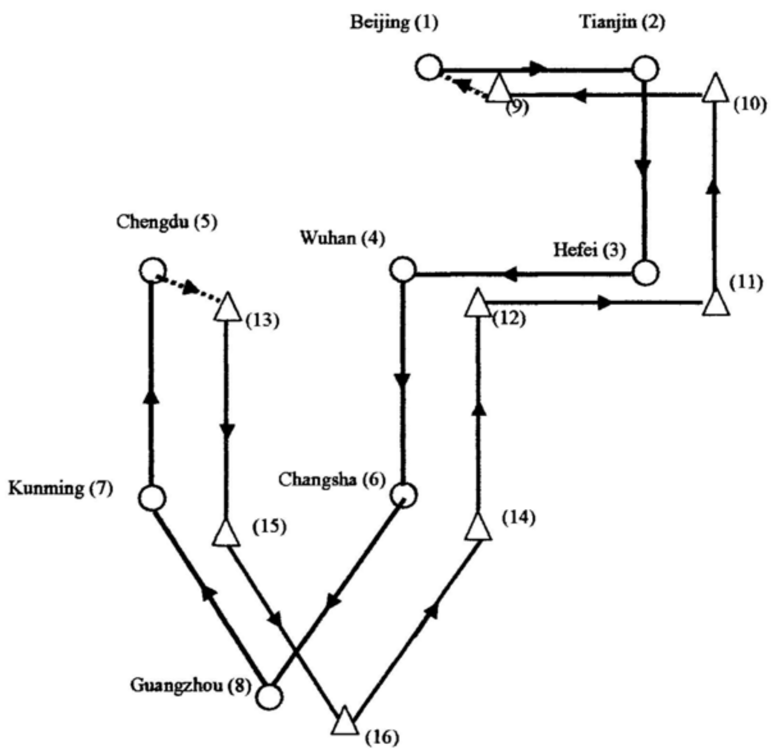

Figure 5.2 Two dual-ring topology networks after merging at CIBC with 16 nodes / 16 links (Case 5 of Table 4.1, IBC=900); solid line: operational fiber link; dotted line: Interconnection Link; ○ & △: node on network A & B.

For Case 5 of Table 4.1 and 4.2 with IBC=900, traffic flow will go in a single direction and only 14 out of the original 36 links are needed to be operational. The actual cost saving is more than 55% with respect to the total cost before merging. From Table 4.2, the interconnection links are also installed at the nodes that are one hop from two most apart articulation nodes (in Case 5, node 9/1 and 5/13 are one hop from single articulation node 4/12). If the articulation node is removed, the network will be divided into two or more sub-networks [12], [52]. If the interconnection links are installed at the same location then the required number of fiber links is 2 L_{min} as shown in Fig. 5.3. Interconnection links installed at the articulation nodes will not be an optimal solution. Details explanation can be found in [12].

If the two interconnection links are installed at two neighboring nodes, two more fiber links can be saved and the total number of fiber links required shall be $2(L_{min} - 1)$ as shown in Fig. 5.4.

If the two interconnection links are installed at the two sides of an articulation node i.e. one hop from the articulation node, it will result in two more links saving in one network. The total number of fiber links required will be $2(L_{min} -2)$. For a network with only one articulation node e.g. the dual-ring network in Fig. 3.1, this is shown to have the maximum saving in fiber links for a merger of the two identical networks [53]. One possible solution is already shown in Fig. 5.2.

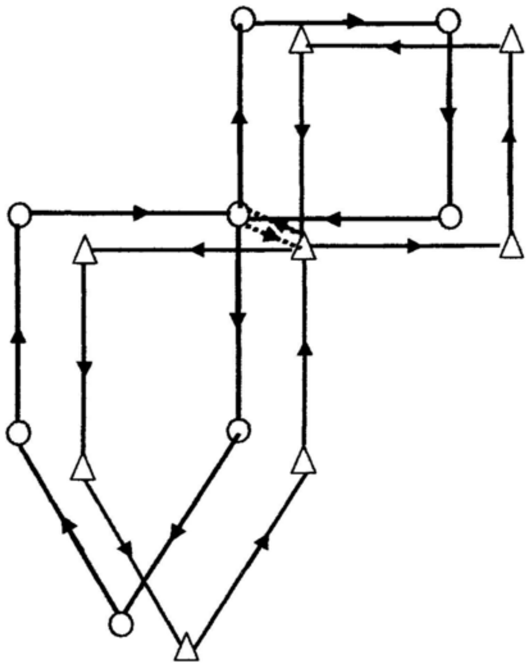

Figure 5.3 Two dual-ring topology networks after merging with two interconnection links at co-located nodes; solid line: operational fiber link; dotted line: Interconnection Link; ○ & △: node on network A & B.

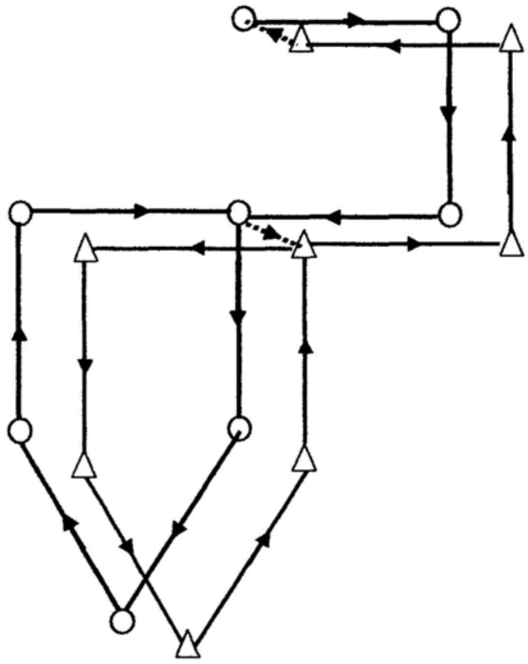

Figure 5.4 Two dual-ring topology networks after merging with two interconnection links at two neighboring nodes; solid line: operational fiber link; dotted line: Interconnection Link; ○ & △: node on network A & B.

5.2 Other Topologies

Case analyses are carried out for the merger of two 8-node networks with different topologies as shown in Fig. 3.1 – Fig. 3.5. These topologies can reflect the difference of more efficient topology as compared with less efficient ones.

5.2.1 Optimal cost

It is depicted in Table 4.11 and Fig. 4.3 that as IBC increases, the percentage of cost saving decreases for all topologies. It will cost more to interconnect. Further interconnection will not be justified as build cost increases. Saving in the operating cost of fiber links will decrease as IBC increases. Further increases in IBC after CIBC will not reduce the number of interconnection links or operational fiber links.

Table 4.12 depicts the relations between IBC and the optimal cost for various topologies. When IBC is low, optimal cost is lower for more efficient topologies. The efficiency is related to the node degree and the type of links. The node degree is defined as the number of links associated with a node. The higher the average node degree, the higher the flexibility in choosing alternative routes to achieve more savings in fiber links. As for the type of links, the bridge links are of particular interest. Two fiber links of opposite directions are needed to provide a connection between the two sub-networks associated with the bridge, thus it is less efficient. A network with less number of bridges will be more efficient in terms of fiber link saving. When IBC is low, more interconnection links can be used and it costs less for the operator to use IC than OFL. Thus, the bus and tree topology will have a higher optimal cost than circle, dual-ring, or mesh topology because fewer alternative routes are available. That results in more operational fiber links needed for the bus and tree topologies.

5.2.2 Interconnection links (IC) and operational fiber links (OFL) required

In Table 4.11 and Fig. 4.5, it is evident that under all topologies as IBC increases, the number of interconnection links decreases to achieve optimal overall cost. The number of interconnection links eventually reduces to a minimum value of two. Therefore, it can be concluded that only two minimum interconnection links are required eventually after CIBC is reached for all topologies shown.

When IBC is greater or equal to CIBC, only two interconnection links need to be built for all topologies. Various topologies have different CIBC e.g. both dual-ring and circle topologies' IBC occur at IBC= 900; tree topology occurs at IBC= 2000; mesh topology occurs at IBC= 1500; and bus topology occurs at IBC= 200.

For the circle topology, Hamiltonian cycle exists when IBC < CIBC. The total number of OFL and IC is 8 OFL+8 IC =16. It is clear that when IBC < CIBC, eight OFL and eight IC are required to maintain connectivity to all nodes. After CIBC, only two interconnection links are required, Hamiltonian path is found and it will require 7+7 =14 OFL to maintain connectivity after the merger of two networks.

For the tree topology, no Hamiltonian cycle or path can be found. There are 7 bridges, therefore only L_{min}= 2×B= 2×7 =14 out of the original 28 OFL are required. Five IC are needed until CIBC is reached. After CIBC, it only requires two interconnection links as other topologies do. However, it will require a larger number of operational fiber links, which is 20.

As for the mesh topology, the large tree size requires a much longer analysis time. From the case analysis, the minimum total number of OFL and IC is 16. More IC (3 to 10) will be used before CIBC is reached. Hamiltonian cycle is found, the minimum number of OFL = number of nodes in one network =8. After CIBC is reached, again only two IC are required. Total number of OFL is 7+7=14.

The bus topology has 7 bridges and therefore needs to use a minimum of 2×7 =14 OFL when IBC is low. It is interesting to note that the flow cost does have an influence upon the final optimal solution when IBC is small as it is noted in Case 1 of Table 4.9. Flow cost again outweigh the build and operational cost of IC, it is therefore more viable to use an extra IC. After CIBC, it is apparent that Hamiltonian path found; only two interconnection links are required and 7+7 =14 OFL is needed for the merger of two bus networks.

5.2.3 Location of interconnection links

Bus topology

On the location of interconnection links, the tree and bus topology will first be considered. It is found that when there are only two interconnection links, the interconnection links generally occur at the two most remote nodes. As illustrated for the bus topology, interconnection locations are at node 1 (with node 9) and node 8 (with node 16) as shown in Fig. 5.5. This is obvious as the two interconnection links and the two bus networks form a unidirectional cycle. The Hamiltonian cycle provides complete connection for any two nodes within the two networks as shown in Fig 5.5.

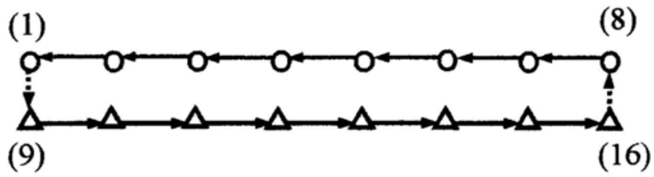

Figure 5.5 Two bus topology networks after merging at CIBC with 16 nodes / 16 links;

solid line: operational fiber link; dotted line: Interconnection Link;

○ & △: node on network A & B.

More generally, for arbitrary topologies, the locations of the two interconnection links when IBC goes beyond CIBC will be analyzed [12]. The path that contains the maximum number of directly connected articulation nodes with different groupings needs to be identified. It is shown that the two interconnection links shall be located at one hop away from the two most separated articulation nodes. This will be one of the optimal solutions for the merging of two networks. It applies to the tree and bus topology of Fig. 3.3 and 3.5.

Tree topology

For the tree topology as shown in Fig. 5.6, one of the interconnection links occurs at node 8 (with node 16) or node 7 (with node 15), while the other interconnection occurs at node 6 (with node 14) or node 5 (with 13). The way to locate the two most remote nodes is to first find a path that contains a maximum number of bridges in the network. The path can only be allowed to pass through the bridges once. The two end nodes of the path are where the interconnection links need to be installed which is one hop away from the two most apart articulation nodes. The reason is quite similar to that of the bus topology. The two interconnection links, the path in network A, and the other identical path in network B form a unidirectional cycle. One half of the fiber links along the original path can be reduced. All nodes, including the nodes that are not located along the path, stay fully connected. The two tree topology networks illustrated in Fig. 3.3 are left-right symmetric. There are four different paths that contain a maximum number of bridges which is 4. This results in the aforementioned four choices of the interconnection locations for the tree topology. These four choices will achieve the same saving in fiber links and optimal cost for a given IBC.

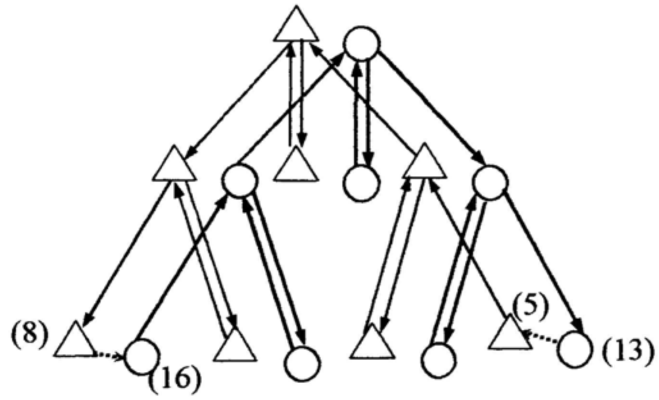

Figure 5.6 Two tree topology networks after merging at CIBC with 16 nodes / 22 links;

solid line: operational fiber link; dotted line: Interconnection Link;

○ & △: node on network A & B.

As discussed earlier under the dual-ring topology, Eq. (9) can also apply to other topologies with interconnection links for all co-located nodes. For the tree network illustrated in Fig. 3.3, all the links are bridges and the minimum number of operational fiber links required is: L_{min}=2B=2×7=14 when IBC is low. As there are totally 28 fiber links in the original two 8-node networks, only 14 of the 28 fiber links are required. 50% of savings in fiber links can be achieved. Only 48% of cost saving is shown in the analysis results because the interconnection build cost (IBC=1) and interconnection operating cost are included in the case analysis.

Dual-ring, circle and mesh topologies

For the dual-ring, circle and mesh topology illustrated in Fig. 3.1, 3.2, and 3.4, it is found that there is a Hamiltonian path that covers all the nodes in one network. A Hamiltonian path of a network may contain articulation nodes or bridges. With two interconnection links installed at the two end nodes of the Hamiltonian path, a unidirectional cycle that connects all the nodes of the two identical networks can be formed. This results in the minimum number of operational fiber links when interconnection links are at a minimum of two. This applies when IBC is higher than CIBC, whereby the total number of OFL and IC is equal to the number of nodes of the two identical networks. For the dual-ring topology, one possible solution is shown in Fig. 5.2. Whereas for the circle topology, any two adjacent nodes (e.g. node (1 and 9) and node (16 and 8)) can be chosen as the interconnection nodes as shown in Fig. 5.7. This will result in a big cycle that covers all nodes in the two networks. In our case study, one possible optimized mesh network is shown in Fig, 5.8. Two Hamiltonian paths are selected and they form a cycle with two interconnection links installed at the end nodes of the Hamiltonian paths.

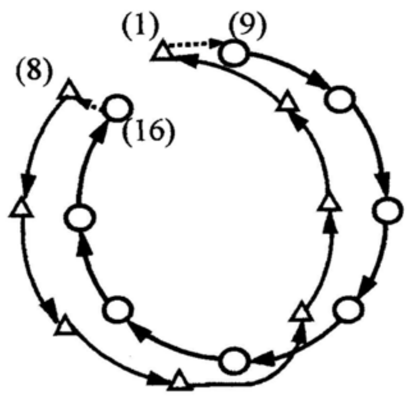

Figure 5.7 Two circle topology networks after merging at CIBC with 16 nodes / 16 links; solid line: operational fiber link; dotted line: Interconnection Link; ○ & △: node on network A & B.

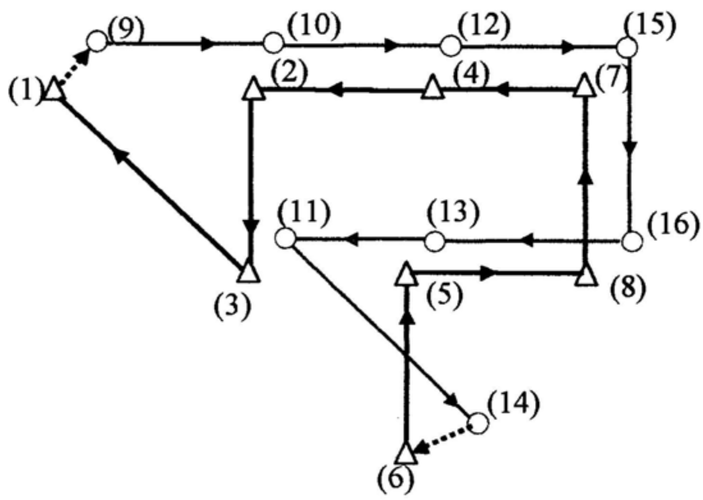

Figure 5.8 Two mesh topology networks after merging at CIBC with 16 nodes/16 links (IBC = 1500 of Table 4.7 & 4.8); solid line: operational fiber link; dotted line: Interconnection Link; ○ & △: node on network A & B.

Likewise in Eq. (9), 75% of savings in fiber links can be achieved for both the dual-ring and the circle topology networks. In this case, when IBC=0, only one direction of the fiber links in one network is preserved. All co-located nodes are equipped with bi-directional interconnection links (total 16 interconnections at 8 locations). Cross network traffic will all be routed through interconnection links as shown in Fig. 5.1. In terms of the number of interconnection links, this is different from case 1 in Table 4.1 (IBC=1), which has only eight interconnection links. While for the mesh network in Fig. 3.4, a maximum of 83.91% cost saving is achieved. The above analysis results again agree with the analytical results on the number of fiber links saved. For these analytical analyses, the solutions are about finding a cycle or multiple cycles that contains all nodes. The cycle or cycles will provide full connectivity for traffic between any two nodes within the two identical networks. It is related to Hamiltonian cycle problems [52]. Similar cycle forming problems can also be found in the design of survival wavelength division multiplexing (WDM) networks [54].

5.3 Summary

The analytical and analysis results are in line for all topologies. Optimal cost increases as IBC increases. Fiber cost saving also decreases as a result of the IBC increase. It is also found that when IBC> CIBC, increases in IBC will not reduce the number of operational fiber links or interconnection links. Therefore, no further saving will occur in terms of fiber links. More efficient topologies will have a lower optimal cost than less efficient ones.

The numbers of OFL and IC are related to node connectivity. The higher the node connectivity, the more the alternative routes available for traffic to be routed. The more efficient the network becomes.

As IBC increases, the number of interconnection links reduces to two as a minimum. The two interconnection links are such that one from one network to the other network and the other link is in reverse direction. For the location of the two interconnection links when IBC exceeds or equal to CIBC, interconnection links shall not be at the same node. If a Hamiltonian path can be found in the network, one of the optimal solutions is to install the two interconnection links at the two ends of the path. The objective is to form a big cycle in order to provide connectivity for all traffic to all nodes of the merged network. Another approach is to identify articulation nodes. When the network contains articulation nodes, the path that contains maximum number of directly connected articulation nodes in different groupings needs to be found. The two interconnection links shall be located at one hop away from the two most separated articulation nodes. Analysis results well support these findings for the identification of optimal interconnection locations for the concerned topologies. These findings will provide a good basis for network planner in their design of merger of two identical networks.

Chapter 6

Extension of the model

The model has been used for the investigation of network consolidation for various topologies and the results are analyzed. The present model in Eq. (1) can be further extended for other considerations. This chapter will present these findings.

6.1 Expandability on the size of network

The viability of the model is firstly examined in terms of expanding on its capacity. The investigated dual-ring network, which is part of a real China network, is expanded to two 16-node topology and its effect to the interconnection and operational fiber links will be shown. Figure 6.1 illustrates the concerned topology. Only one network of the two identical networks (network A and B) is shown. Notation (*a*, *b*) represents co-located nodes with node *a* in network A and node *b* in network B.

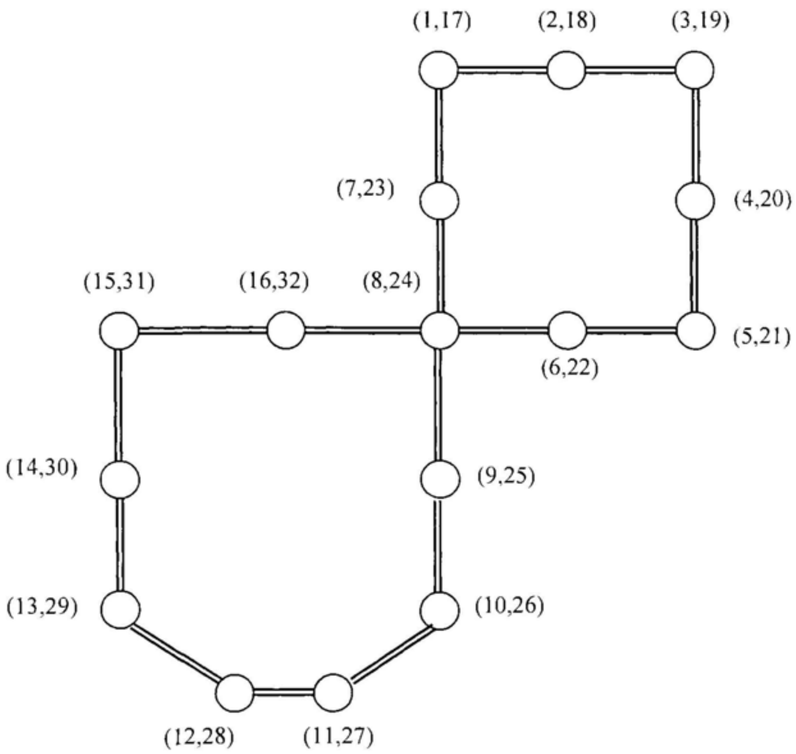

Figure 6.1 Two dual-ring topology networks with 32 nodes/68 links

Node (*a*, *b*) is node *a* in network A and node *b* in network B

Figure 6.1 illustrates the expanded network derived by adding an addition node to each and every fiber link of the network shown in Fig. 3.1. The network is expanded to a total of 32 nodes and 68 links. A 32-node network for a backbone infrastructure is a sizable network.

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	28478	68	19	68000	19000	49000	30	3030	45970	67.60%
2	600	34427	68	27	68000	27000	41000	12	8400	32600	47.94%
3	800	37270	68	27	68000	27000	41000	12	10800	30200	44.41%
4	900	38363	68	30	68000	30000	38000	2	2000	36000	52.94%
5	1500	40680	68	32	68000	32000	36000	2	3200	32800	48.23%

Table 6.1 Optimal Cost vs. Interconnection Build Cost (IBC)

for two dual-ring networks with 32 nodes/68 links

OFL: Operational Fiber Link; IC: Interconnection Link

Table 6.1 highlights the increase in optimal cost as IBC increases. Operational fiber links reduces from 68 to 19 for case 1 when IBC is 1. 30 IC are being used for this situation. Fiber operating cost can be reduced by over 67%. A bigger tree size for this network requires longer computation time. As from Eq. (9) of section 5.1.2, the minimum number of fiber links required after the merger of the two expanded dual-ring network is $L_{min} = 0 + 16 + 1(2\text{-}1) = 17$. With enough computation time, we should be able to reach 17 OFL and 17 IC for IBC=1 without taken into account of flow cost. Flow cost in this case influences the outcome of the optimal solution. More savings in flow cost will occur by using more IC, since one IC only costs 100+1 =101 when IBC is 1.

Fiber cost saving in Table 6.1 is within range with the cost saving of Table 4.1. CIBC both occurs at 900 and only two interconnection fiber links are required. From the discussion in section 5.1.3, one of the two interconnection links shall occur at node 6 (with node 22) or node 7 (with node 23) and the other at node 9 (with node 25) or node 16 (with node 32). All the four choices of interconnections will result in a minimum number of 30 operational fiber links.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	2/1, 1/7, 3/2, 4/3, 5/4, 6/5, 8/6, 7/8, 8/16, 9/8, 10/9, 11/10, 12/11, 13/12, 14/13, 15/14, 16/15, 18/19, 25/26	19	1/17, 17/1, 2/18, 18/2, 3/19, 19/3, 4/20, 20/4, 5/21, 21/5, 6/22, 22/6, 7/23, 23/7, 8/24, 24/8,9/25,26/10,11/27, 27/11, 12/28, 28/12, 13/29, 29/13, 14/30, 30/14, 15/31, 31/15, 16/32, 32/16	30	30
2	600	1/2, 7/1, 2/3, ¾, 4/5, 5/6, 16/8, 8/9, 9/8, 11/10, 12/13, 13/14, 14/15, 15/16, 17/18, 20/19, 21/20, 22/24, 24/22, 24/23, 24/32, 26/25, 28/27, 29/28, 30/29, 31/30, 32/31	27	1/17, 18/2, 19/3, 5/21, 6/22, 22/6, 23/7, 8/24, 25/9, 10/26, 27/11, 28/12,	12	7200

3	800	7/1, 2/3, 5/4, 5/6, 6/8, 8/7, 8/16, 10/9, 1/10, 11/12, 13/12, 14/13, 14/15, 16/15, 17/18, 19/18, 19/20, 20/21, 24/22, 17/23, 24/25, 32/24, 25/26, 26/27, 28/29, 29/30, 31/32	27	1/17, 18/2, 3/19, 4/20, 21/5, 22/6, 23/7, 9/25, 27/11,12/28, 30/14, 15/31	12	9600
4	900	1/2, 7/1, 2/3, ¾, 4/5, 5/6, 8/7, 16/8, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16, 18/17, 19/18, 20/19, 21/20, 22/21, 23/24, 17/23, 24/32, 26/25, 27/26, 28/27, 29/28, 30/29, 31/30, 32/31	30	6/22, 25/9	2	1800
5	1500	2/1, 1/7, 3/2, 4/3, 5/4, 6/5, 8/6, 7/8, 8/9, 9/10, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16, 17/18, 18/19, 19/20, 20/21, 21/22, 22/24, 24/23, 23/17, 25/24, 26/25, 27/26, 28/27, 29/28, 30/29, 31/30, 32/31	32	24/8, 16/32	2	3000

Table 6.2 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for two dual-ring topology with 32 nodes/68 links.

Table 6.2 shows that at CIBC, the required interconnection links are two. The minimum number of operational fiber links and interconnection links are 15+15=30. The two interconnection links are located at node (25, 9) and (6, 22) that is one hop away from the articulation node (8, 24). This is in line with the conclusion for the smaller dual-ring topology network in Fig. 3.1.

Based on the above findings, the larger dual-ring network analysis results arrive at the same findings as the smaller dual-ring network. Therefore, the model can cater for larger network application.

6.2 Other real networks

Other real networks are examined to further verify the applicability of our proposed model. The Abilene and the NSFNET networks are used with the same parameters and assumptions made as the dual-ring topology. We then examine the real data from the China network so that we can see the effect of using real data onto our model.

6.2.1 The Abilene network

The Abilene network in Figure 6.2 is one of the networks in the U.S.A. It comprises of 11 nodes and 28 links. With two identical fiber optical networks, a total of 22 nodes and 56 fiber links are being examined.

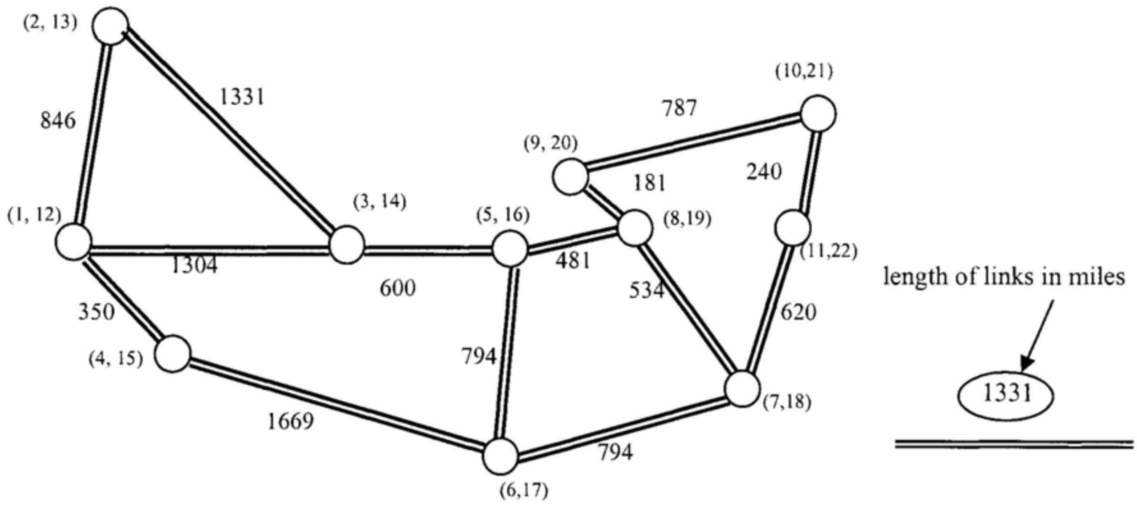

Figure 6.2 Two Abilene networks with 22 nodes / 56 links

Node (a,b) is node a in network A and node b in network B

Number on fiber links is the distance between nodes

The analysis results for the Abilene network are shown in Tables 6.3 and 6.4.

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	142583	56	13	56000	13000	43000	15	1515	41485	74.08%
2	800	242988	56	12	56000	12000	44000	10	9000	35000	62.50%
3	900	253874	56	18	56000	18000	39000	4	4000	34000	60.71%
4	1000	255195	56	20	56000	20000	36000	2	2200	33800	60.36%
5	10000	364368	56	20	56000	20000	36000	2	20200	15800	28.21%

Table 6.3 Optimal Cost vs. Interconnection Build Cost (IBC) for Abilene Network

OFL: Operational Fiber Link; IC: Interconnection Link

Optimal cost increases as IBC increases. The large tree size requires long computation time. Over 74% of fiber cost saving can be achieved through the merger of two Abilene networks. Cost saving is minimum after CIBC occurs.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	1/2, 5/3, 9/8, 10/9, 11/10, 13/12, 12/15, 14/13, 15/17, 19/16, 17/18, 21/20, 18/22	13	12/1, 2/13, 3/14, 14/3, 4/15, 15/4, 16/5, 6/17, 17/6, 7/18, 18/7, 8/19, 20/9, 10/21, 22/11	15	15

2	800	2/1, 1/3, 5/8, 6/4, 9/10, 11/7, 12/13, 15/12, 14/16, 18/17, 19/20, 21/22	12	13/2, 3/14, 4/15, 16/5, 17/6, 7/18, 8/19, 20/9, 10/21, 22/11	10	8000
3	900	3/1, 1/4, 2/3, 6/5, 8/7, 4/6, 9/8, 11/10, 7/11, 14/13, 15/12, 12/14, 17/15, 16/19, 18/17, 19/20, 22/18, 21/22	18	13/2, 5/16, 20/9, 10/21	4	3600
4	1000	2/1,4/6, 3/2, 5/3, 6/7,7/11, 8/5, 9/8, 10/9, 11/10,12/13, 13/14, 14/16, 16/19, 17/15, 18/17, 19/20, 20/21, 21/22, 22/18	20	1/12, 15/4	2	2000
5	10000	1/4, 3/2, 5/3, 8/5, 6/7, 4/6, 9/8, 10/9, 11/10, 7/11, 15/12, 13/14, 14/16, 17/15, 16/19, 18/17, 19/20, 20/21, 21/22, 22/18	20	12/1, 2/13	2	20000

Table 6.4 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for Abilene Network

A minimum of 22 OFL and IC is required when IBC=800 to 10000 as the total number of nodes of two networks is 22. Again after CIBC, only two interconnection links will be required for interconnection. A Hamiltonian path is found, number of required OFL is 10 +10 =20. Fig. 6.3 shows the resultant 20 OFL and two IC for Case 4. In Case 3, the total number of OFL and IC is 22. It is also deviated analytically that the minimum number of operating fiber links is 22 (Total OFL + IC = number of nodes of two networks = 22). Both analytical and analysis results concur with each other.

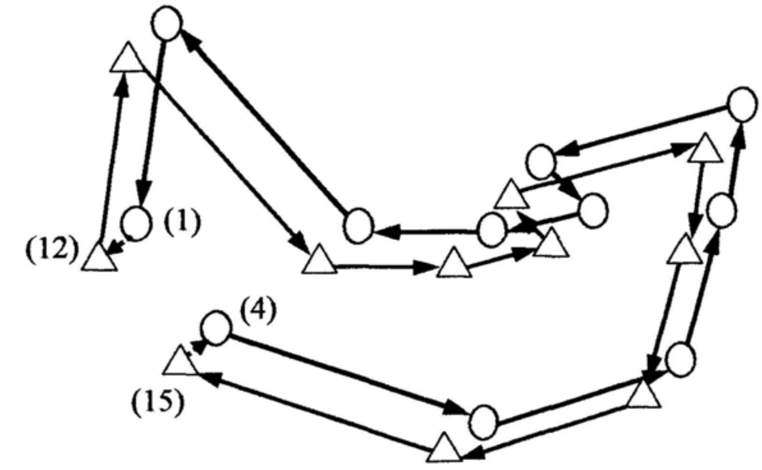

Figure 6.3 Two Abilene networks after merging at CIBC with 22 nodes / 22 links;

solid line: operational fiber link; dotted line: Interconnection Link;

○ & △: node on network A & B.

6.2.2 The NSFNET network

The NSFNET 1995 network is used for case studies. Fig. 6.4 shows the network. It comprises of 13 nodes and 32 links. A duplicated network will comprise of 26 nodes and 64 fiber links. This again is a sizable backbone network for case analysis.

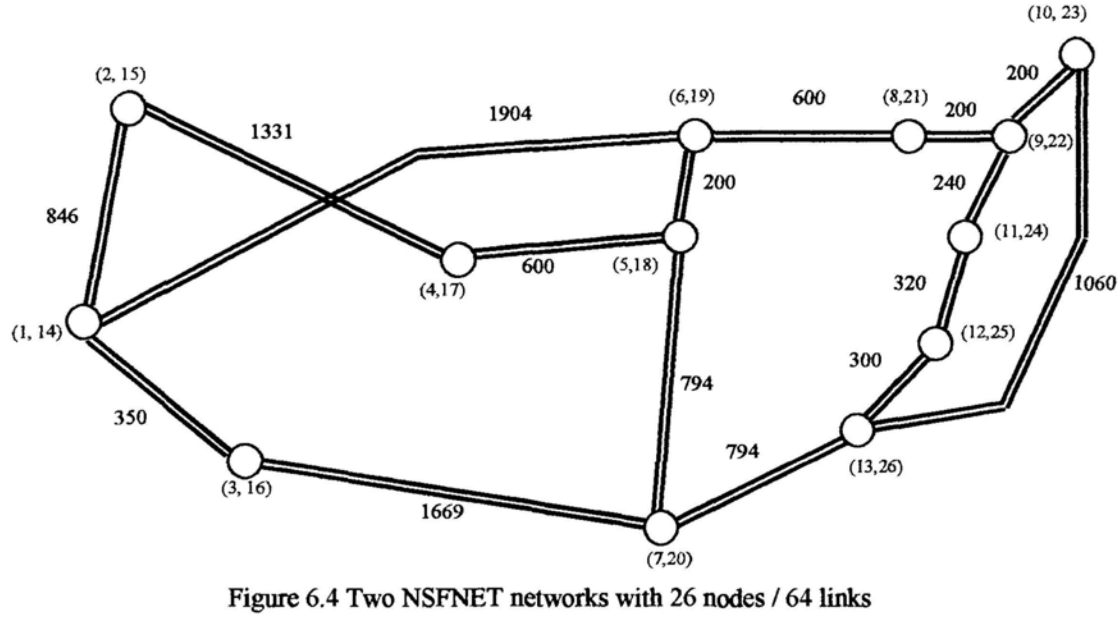

Figure 6.4 Two NSFNET networks with 26 nodes / 64 links

Node (a,b) is node a in network A and node b in network B

Number on fiber links is the distance between nodes

The NSFNET network is similar to the Abilene network. It contains more nodes. It again has a large tree size. Computation time is very long. The results are shown in Tables 6.5 and 6.6.

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	22503	64	14	64000	14000	50000	15	1515	48485	75.76%
2	1000	30466	64	24	64000	24000	40000	3	3300	36700	57.34%
3	2000	36856	64	24	64000	24000	40000	2	4200	35800	55.93%

Table 6.5 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for NSFNET Network

OFL: Operational Fiber Link; IC: Interconnection Link

Table 6.5 illustrates that over 75% fiber cost saving can be achieved when IBC=1. After IBC reaches 2000, there are still over 55% fiber link savings with only two interconnection links are used.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	1/2, 5/6, 7/3, 8/9, 9/10, 9/11, 12/13, 15/17, 16/14, 17/18, 19/21, 23/22, 24/25, 26/20	14	2/15, 3/16, 4/17, 5/18, 6/19, 10/23, 11/24, 13/26, 14/1, 17/4, 18/5, 20/7, 21/8, 22/9, 25/12	15	15
2	1000	1/2, 2/4, 3/1, 4/5, 5/6, 6/8, 7/13, 8/9, 9/10, 11/9, 12/11, 13/12, 14/16, 15/14, 17/15, 18/17, 19/18, 21/19, 22/21, 22/24, 23/22, 24/25, 25/26, 26/20	24	10/23, 16/3, 20/7	3	3000
3	2000	1/2, 2/4, 4/5, 5/7, 6/1, 7/3, 8/6, 9/8, 10/13, 11/9, 12/11, 13/12, 14/19, 15/14, 16/20, 17/15, 18/17, 19/21, 20/18, 21/22, 22/24, 24/25, 25/26, 26/23	24	3/16, 23/10	2	4000

Table 6.6 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for NSFNET Network

In Table 6.6, it shows that 24 OFL are used in Case 3 after CIBC is reached. It again shows that two interconnection links for interconnection are used when IBC is large. For the location for the two interconnections, from the discussion in section 5.2.3, it is also found that there is a Hamiltonian path that covers all the nodes in the NSFNET network. One possible path is as the following: node 10 → 13 → 12 → 11 → 9 → 8 → 6 → 1 → 2 → 4 → 5 → 7 → 3. With two interconnection links installed at the two end nodes of the Hamiltonian path, a unidirectional cycle that connects all the nodes of the two networks can be formed. This results in minimum operational fiber links when interconnection links are as at its minimum of two. One solution is illustrated in Case 3 of Table 6.6 as shown in Fig. 6.5. This results in 56% of cost saving. It is conclusive that substantial fiber links savings are possible with the merger of two optical networks.

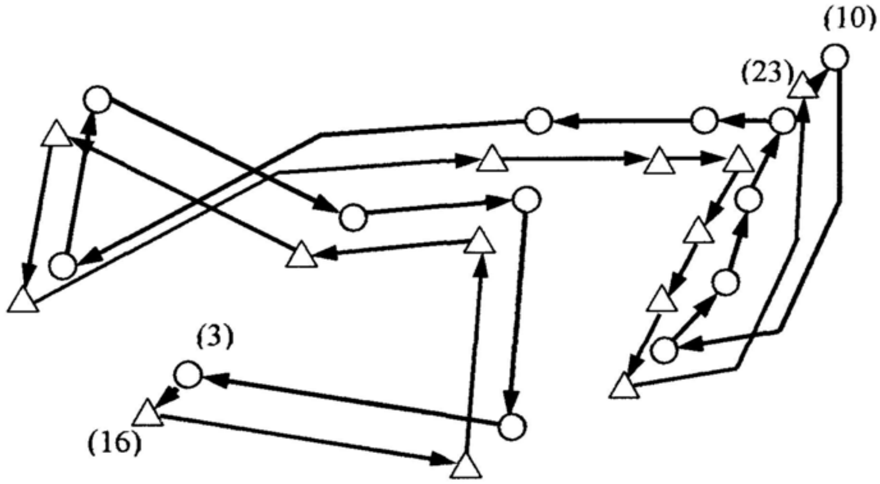

Figure 6.5 Two NSFNET networks after merging at CIBC with 26 nodes / 26 links;

solid line: operational fiber link; dotted line: Interconnection Link;

○ & △: node on network A & B.

6.2.3 The China network with real data

Whole network

In this section, real data of a China dual-ring topology network is used to illustrate the applicability of the proposed model in real situations. The network comprises of two 10-Gb/s rings and two 2.5-Gb/s rings as shown in Figure 6.6. It contains a total of two 12-node and 28-link networks. A total of 24 nodes and 56 links are being analyzed.

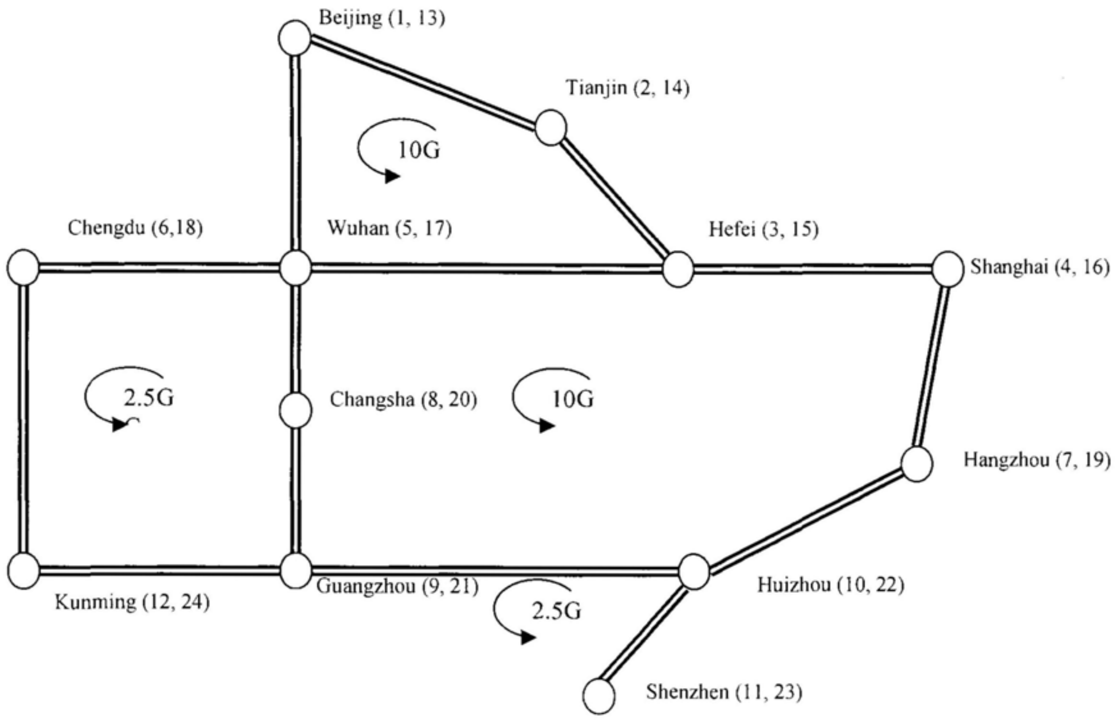

Figure 6.6 Two China real networks with 24 nodes / 56 links

Node (*a*, *b*) is node *a* in network A and node *b* in network B

Equipment cost used is based upon the actual cost used on each node. This varies from node to node e.g. Beijing is \$344,000 and Wuhan is \$570,000. The more equipment locates at the node, the more operating cost will incur. Equipment capacity depends on the equipment installed at the node e.g. Wuhan has more equipment than Beijing therefore node cost in Wuhan is higher than Beijing. Flow cost is still assumed to be 1. Fiber link operation cost will depend on the length of the fiber links between nodes. It is assumed to be at US\$8.70/km, thus Beijing to Tianjin is US\$870 and Beijing to Wuhan is US\$13050. Fiber capacity is again very large i.e. 1000 is used. Interconnection build cost at co-located node varies, since the distance between interchanges differs in different co-located nodes e.g. In Beijing, it is \$35,000 and in Hangzhou, it is \$70,000. Some of these parameters are listed in

Tables 6.7.1 and 6.7.2 for reference. The build cost of existing fiber links is not considered since we are analyzing existing networks. Other assumptions remain unchanged.

Parameters	Fiber Links	Fiber Build Cost US $ ('00)	Fiber Operating Cost US $ ('00)
Interconnection Links	1/13,13/1	350	0.87
	2/14,14/2	385	0.96
	3/15,15/3	455	1.13
	4/16,16/4	525	1.31
	5/17,17/5	455	1.13
	6/18,18/6	595	1.48
	7/19,19/7	700	1.74
	8/20,20/8	455	1.13
	9/21,21/9	525	1.31
	10/22,22/10	595	1.48
	11/23,23/11	490	1.22
	12/24,24/12	420	1.04
OFL	1/2,2/1,13/14,14/13	0	8.70
	1/5,5/1,13/17,17/13	0	130.50
	2/3,3/2,14/15,15/14	0	98.31
	3/4,4/3,15/16,16/15	0	58.03
	3/5,5/3,15/17,17/15	0	53.94
	4/7,7/4,16/19,19/16	0	29.58
	5/6,6/5,17/18,18/17	0	167.04
	5/8,8/5,17/20,20/17	0	38.28
	6/12,12/6,18/24,24/18	0	100.92
	7/10,10/7,19/22,22/19	0	181.83
	8/9,9/8,20/21,21/20	0	73.08
	9/10,10/9,21/22,22/21	0	15.66
	9/12,12/9,21/24,24/21	0	165.30
	10/11,11/10,22/23,23/22	0	7.83

Table 6.7.1 Parameters for the Real China Network: Fiber Link and its Values (f_{ij})

Node	Node Build and Operating Cost US$ ('000) e_i	Equipment Capacity (Gb/s) q_i
1	344	10
2	252	10
3	450	20
4	328	10
5	570	22.5
6	88	2.5
7	246	10
8	286	12.5
9	422	12.5
10	238	10
11	266	10
12	54	2.5
13	246	10
14	240	10
15	474	20
16	250	10
17	438	22.5
18	230	2.5
19	272	10
20	432	12.5
21	440	12.5
22	226	10
23	272	10
24	244	2.5

Table 6.7.2 Parameters for the Real China Network: Node Cost (e_i) and its Equip. Capacity (q_i)

Tables 6.7.1 and 6.7.2 show the parameters and real data used of fiber links and nodes for the real China network. The results are shown in the following Tables 6.8 and 6.9.

Case	No. of commodity	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)		(j)= (g)-(i)	(k)=(j)/(e)
1	24	26195	56	27	451600	184562	267038	2	80700	186338	41.26%
2	28	34444	56	32	451600	241895	209705	2	91226	118479	26.24%
3	32	35877	56	33	451600	277913	173687	2	91226	82461	18.24%

Table 6.8 Optimal Cost vs. Commodity Size for China Network with 24 nodes and 56 links

OFL: Operational Fiber Link; IC: Interconnection Link

Table 6.8 shows the results when we vary the number of the commodities within the real network. IBC is known and relatively expensive compared with fiber operating cost in this case analysis. Therefore, IBC exceed CIBC and only two interconnection links is required. Since more traffic is going through within the network from Case 1 to 3, optimal cost increases as a result of the increase in traffic. In this case, fiber operating cost is distance dependant. Fiber cost saving of the China network after merging is less than 45%. All savings and IBC and IC costs are calculated based on actual data.

Case	Commodity size	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC	IC Op. Cost
1	24	2/1, 3/2, 3/4, 4/7, 5/3, 5/6, 6/12, 7/10, 8/5, 9/8, 10/9, 10/11, 11/10, 12/9, 13/14, 14/15, 15/17, 16/15, 17/20, 18/24, 19/16, 20/21, 21/22, 22/19, 22/23, 23/22, 24/21	27	17/5, 1/13	2	80500	200
2	28	1/2, 1/5, 2/1, 3/4, 3/5, 4/7, 5/1, 5/6, 5/8, 6/5, 7/10, 8/5, 9/8, 10/11, 11/10, 10/9, 12/9, 13/14, 14/15, 15/17, 16/15, 17/13, 17/20, 18/17, 19/16, 20/21, 21/22, 21/24, 22/19, 22/23, 23/22, 24/18	32	5/17, 15/3	2	91000	226
3	32	1/5, 2/1, 3/2, 3/4, 4/3, 5/3, 5/6, 5/8, 6/5, 7/4, 8/5, 8/9, 9/10, 9/12, 10/7, 10/11, 11/10, 12/9, 13/14, 14/15, 15/17, 15/16, 16/19, 17/13, 17/18, 18/24, 19/22, 20/17, 21/20, 22/21, 22/23, 23/22, 24/21	33	3/15, 17/5	2	91000	226

Table 6.9 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Commodity Size for China Network

Table 6.9 shows that the minimum OFL and IC are 35 links for Case 3 and 29 links for Case 1. However, it only requires two interconnection fiber links for all the cases.

In addition to the varying of number of commodities in the network, the flow size in the real network is also varied to see the effect it has on the interconnection. This is shown in Tables 6.10 and 6.11.

Case	Flow Size	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Opera-ting Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)	(j)= (g)-(i)	(k)=(j)/(e)
1	0.4	25818	56	26	451600	173922	277678	2	84209	193469	42.84%
2	0.6	26195	56	27	451600	184562	267038	2	80700	186338	41.26%
3	0.8	27264	56	27	451600	184153	267447	2	80700	186747	41.35%
4	1.2	27285	56	27	451600	202136	249464	2	80700	168764	37.37%

Table 6.10 Optimal Cost vs. Flow Size

for China Network with 24 nodes and 56 links

OFL: Operational Fiber Link; IC: Interconnection Link

As the flow size is small, the optimal cost decreases. In all cases, the required interconnection links are only two.

Case	Flow Size	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	IBC	IC Op. Cost
1	0.4	2/1, 3/2, 3/4, 4/3, 4/7, 5/3, 5/6, 6/5, 7/4, 8/5, 9/8, 10/9, 11/10, 12/6, 13/14, 14/15, 15/16, 16/19, 17/15, 18/17, 19/22, 20/17, 21/20, 22/21, 22/23, 24/18	26	1/13, 23/11	2	84000	200
2	0.6	2/1, 3/2, 3/4, 4/7, 5/3, 5/6, 6/12, 7/10, 8/5, 9/8, 10/9, 10/11, 11/10, 12/9, 13/14, 14/15, 15/17, 16/15, 17/20, 18/24, 19/16, 20/21, 21/22, 22/19, 22/23, 23/22, 24/21	27	1/13,17/5	2	80500	200

3	0.8	2/1,3/2,3/4,4/7,5/3,5/6,6/12,7/10,8/5,9/8, 10/11,11/10,12/9,13/14,14/15,15/16,16/19, 17/15,18/24,19/22,20/17,21/20, 22/21,22/23,23/22,24/21	27	1/13,15/3	2	80500	200
4	1.2	2/1,3/2,3/4,4/7,5/3,5/6,6/12,7/10,8/5,9/8, 10/9,10/11,11/10,12/9,13/14,14/15,15/17, 16/15,17/20,18/17,19/16,20/21, 21/22,22/19,22/23,23/22,24/18	27	1/13,17/5	2	80500	200

Table 6.11 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Flow Size for China Network

Tables 6.10 and 6.11 show how the model operates under real conditions with variation in fiber and node operating costs. Different interconnection build costs and node capacities are also considered. It will identify the operational fiber links needed and the specific location of the interconnection links that will provide the most optimal cost for the operator. In the following section, a reduced China network as shown in Figure 6.7 is used for the analysis with more detailed study on the effect of IBC.

Reduced version of the China network

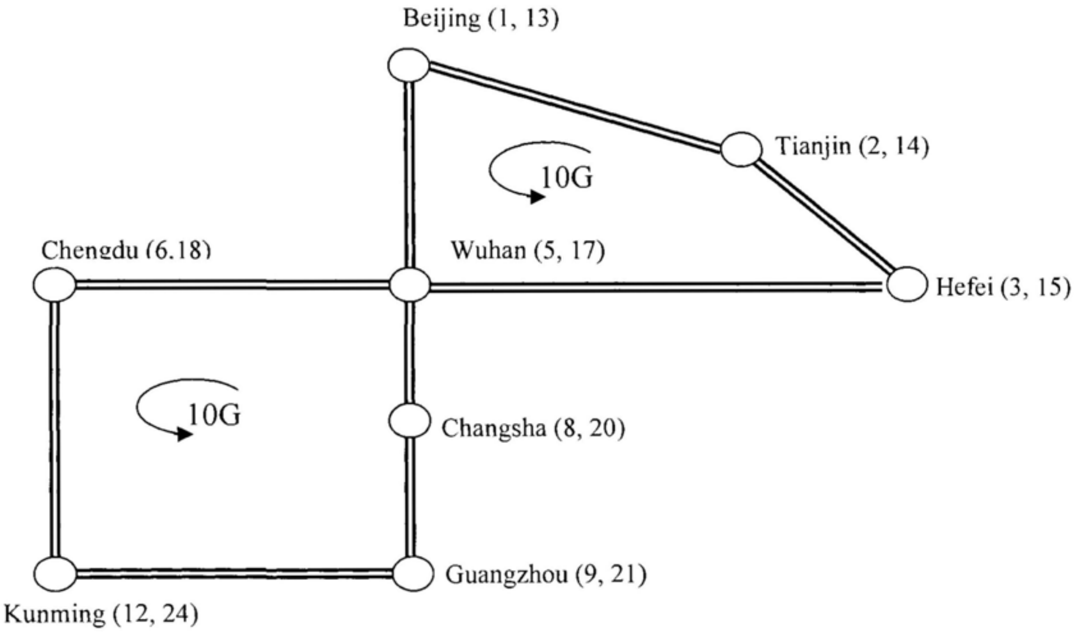

Figure 6.7 Reduced version of the real China network with 16 nodes and 36 links

Node (a,b) is node a and b in network A and network B respectively

Fig. 6.7 is the reduced China network for case studies and real data from Tables 6.7.1 and 6.7.2 are used for this purpose. Here we try to investigate the effects of IBC on the optimization. Finer granularity on the IBC is given in the analysis. Table 6.12 illustrates the result of this case study.

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)= (j)/(e)
1	1	93280	36	9	334428	83607	250821	16	1826	248995	74.45%
2	400	93818	36	9	334428	83607	250821	8	4105	246716	73.77%
3	4000	121650	36	11	334428	86652	247776	6	24731	223045	66.69%
4	8000	130300	36	14	334428	107706	226722	2	16235	210487	62.94%
5	20000	158580	36	14	334428	107706	226722	2	40235	186487	55.76%
6	40000	198579	36	14	334428	107706	226722	2	80235	146487	43.80%
7	60000	238579	36	14	334428	107706	226722	2	120235	106487	31.84%
8	80000	278580	36	14	334428	107706	226722	2	160235	66787	19.88%
9	400000	918580	36	14	334428	107706	226722	2	800235	(573513)	No saving

Table 6.12 Optimal Cost vs. Interconnection Build Cost (IBC)

for China Network with 16 nodes and 36 links

OFL: Operational Fiber Link; IC: Interconnection Link

Table 6.12 illustrates that when IBC=1, only 9 operational fiber links are required. All nodes are connected. In the real situation, the number of IC decreases as IBC increases. Once the IBC reaches the CIBC in Case 4, only two interconnection links are required. Optimal cost increases as IBC increases. It is noted that over 74% fiber cost savings can be achieved with this topology when IBC=1.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC + IC
1	1	1/2, 2/3, 3/5, 5/1, 5/8, 6/5, 8/9, 9/12, 12/6	9	1/13, 2/14, 3/15, 5/17, 6/18, 8/20, 9/21, 12/24, 13/1, 14/2, 15/3, 17/5, 18/6, 20/8, 21/9, 24/12	16	1826
2	400	1/2, 3/5, 6/12, 9/8, 14/15, 17/13, 17/18, 20/17, 24/21	9	2/14, 5/17, 8/20, 12/24, 13/1, 15/3, 18/6, 21/9	8	4105
3	4000	1/2, 2/3, 3/5, 5/8, 9/12, 14/13, 15/14, 17/15, 18/17, 20/21, 24/18	11	6/18, 8/20, 12/24, 13/1, 18/6, 21/9	6	24731
4	8000	2/1, 3/2, 5/3, 13/14, 14/15, 15/17, 8/5, 17/20, 9/8, 20/21, 12/9, 21/24, 6/12, 24/18	14	1/13, 18/6	2	16235
5	20000	2/1, 3/2, 5/3, 6/12, 8/5, 9/8, 12/9, 13/14, 14/15, 15/17, 17/20, 20/21, 21/24, 24/18	14	1/13, 18/6	2	40235
6	40000	2/1, 3/2, 5/3, 6/12, 8/5, 9/8, 12/9, 13/14, 14/15, 15/17, 17/20, 20/21, 21/24, 24/18	14	1/13, 18/6	2	80235
7	60000	2/1, 3/2, 5/3, 6/12, 8/5, 9/8, 12/9, 13/14, 14/15, 15/17, 17/20, 20/21, 21/24, 24/18	14	1/13, 18/6	2	120235
8	80000	2/1, 3/2, 5/3, 6/12, 8/5, 9/8, 12/9, 13/14, 14/15, 15/17, 17/20, 20/21, 21/24, 24/18	14	1/13, 18/6	2	160235
9	400000	2/1, 3/2, 5/3, 6/12, 8/5, 9/8, 12/9, 13/14, 14/15, 15/17, 17/20, 20/21, 21/24, 24/18	14	1/13, 18/6	2	800235

Table 6.13 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for China Network

When interconnection links are two, both interconnections are located at one hop from the articulation node. From the case studies, the two interconnection links occur at Beijing and Chengdu. This is one of the optimal solutions for this analysis.

This section shows the applicability of the model for the real network. Some modification to the model to take into account of the node degree and connectivity will be discussed in the next section. Results again concur with the previous result of the dual-ring topology analysis.

6.3 Node cost and node degree

As discussed earlier in the real life situation, node cost is in relationship with the equipment installed at the node. The node will cost more when more equipment is installed. The more connectivity of the node, the more line cards and equipment are needed. The model can then be adjusted to take into account of node connectivity. The amended model can be as follows:

$$C = \sum_{1\le k\le K} \sum_{(i,j)\in A} c_{ij}^k x_{ij}^k + \sum_{(i,j)\in A} f_{ij} y_{ij} + \sum_{i\in V} n_i d_i \cdot z_i \qquad (10)$$

In Eq. (10), the term d_i is added into the node parameter. d_i is the degree of node i. d_i can be expressed as $d_i = \sum_{j\in V} y_{ij} + \sum_{j\in V} y_{ji}$. Here y_{ij} is fiber link from node i to any other node j. n_i is the unit cost per degree for node i. In the case studies, we assume n_i to be uniform for all nodes. It is also possible to consider those costs as cost on links, so that the model remains as a linear model. All other constraints and parameters remain as before.

6.3.1 Mesh topology

Mesh topology as in Fig. 3.4 example is used for this case study. This is presented in Table 6.14.

The total network operating cost before merging, e in Table 6.14 is given as: (the number of OFL before merging × OFL operating cost) + node cost. The total node degree of all the nodes is twice the number of OFL before merging because one fiber link contributes two degrees with its two ends. Therefore, the node cost can be described as: (n_i × number of OFL before merging × 2). For examples: In Case 1 of Table 6.14, e is 56×1000+100×56×2=67200.

The total network operating cost after merging in Table 6.14 is g = 2 (d + f) × n_i + (d × OFL operating cost) + [f × (IBC + IC operating cost)]. The total number of node degrees for all the nodes is 2 (d + f), which is twice the total number of OFL+IC. The total OFL operating cost is d × 1000. The total interconnection build cost and operating cost is f × (IBC + 100). Since flow cost is negligible in the case studies, it is excluded in the calculation of the total network operating cost after merging. For example: In Case 1, g is 2×100×(8+10) +1000×8+10×(1+100)=12610.

Case	IBC	Node Unit cost n_i	No. of OFL Required		Total Operating Cost before Merging	No of IC	Total Operating Cost after Merging	% of Cost Saved (%)
			Before Merging	After Merging				
	a	b	c	d	e = c×1000 + b×2×c	f	g = b×2×(d+f) + 1000×d + f×(a+100)	h = (e-g)/e
1	1	100	56	8	67200	10	12610	81.24
2	1	1000	56	8	168000	10	45010	73.21
3	1	3000	56	8	392000	8	104808	73.26
4	800	100	56	8	67200	8	18400	72.62
5	800	1000	56	8	168000	8	47200	71.90
6	900	100	56	12	67200	4	19200	71.43
7	900	1000	56	12	168000	4	19200	71.43
8	1000	100	56	14	67200	2	19400	71.13
9	1000	1000	56	14	168000	2	48200	71.31
10	2000	100	56	14	67200	2	21400	68.15
11	2000	1000	56	16	168000	2	56200	66.55

Table 6.14 Optimal Cost vs. Interconnection Build Cost (IBC) and Node Unit Cost for mesh topology network

OFL: Operational Fiber Link; IC: Interconnection Link; IBC: Interconnection Build Cost

The revised objective function, Eq. (10), includes node degree as one of the parameters in the model. Table 6.14 illustrates the operating cost before and after merging of two optical networks. Fiber savings reduce as IBC increases. IBC is still one of the dominating factors in the amount of fiber links saving. Further studies in this area are needed to arrive at conclusive results.

Case /link	Node Unit Cost (n_i)	IBC	Operational Fiber Links	No. of OFL	Interconnection Links	No. of IC
1	100	1	1/3, 5/4, 6/8, 8/7, 10/9, 11/14, 12/10, 15/13	8	2/10, 3/11, 4/12, 7/15, 8/16, 9/1, 10/2, 13/5, 14/6, 16/8	10
2	1000	1	1/3, 6/8, 7/5, 10/9, 11/14, 12/10, 13/12, 16/15	8	2/10, 3/11, 4/12, 5/13, 8/16, 9/1, 10/2, 12/4, 14/6, 15/7	10
3	3000	1	1/3, 5/2, 6/8, 7/4, 10/9, 11/14, 12/13, 16/15	8	2/10, 3/11, 4/12, 8/16, 9/1, 13/5, 14/6, 15/7	8
4	100	800	1/3, 4/2, 10/9, 5/2, 7/4, 12/13, 16/15, 11/14	8	2/10, 3/11, 5/13, 8/16, 9/1, 12/4, 14/6, 15/7	8
5	1000	800	7/5, 1/3, 4/2, 6/8, 10/9, 11/14, 13/12,16/15	8	5/13, 14/6, 2/10, 3/11, 8/16, 9/1 ,12/4, 15/7	8
6	100	900	2/5, 3/1, 4/2, 6/3, 7/4, 8/7, 9/10, 11/14, 13/11, 10/12, 12/15, 15/16,	12	1/9, 5/13, 14/6, 16/8	4
7	1000	900	2/5,3/1,4/2,6/3,7/4,8/7,9/10, 10/12,11/14,12/15,13/11,15/16	12	1/9,5/13,14/6,16/8	4
8	100	1000	2/3, 3/1, 4/2, 5/4, 6/8, 7/5, 8/7, 9/10, 10/12, 11/14, 12/15, 13/11, 15/16, 16/13	14	1/9, 14/6	2
9	1000	1000	1/3, 2/5, 3/6, 4/2, 6/8, 7/4, 8/7, 10/9, 11/14, 12/10, 13/11, 14/16, 15/12, 16/15	14	5/13, 9/1	2
10	100	2000	1/2, 2/5, 3/1, 4/7, 5/4, 6/3, 8/6, 9/11, 10/9, 11/14,12/10, 13/12, 14/16, 15/13	14	7/15, 16/8	2

11	1000	2000	2/5, 3/1, 4/2, 5/7, 6/3, 7/4, 7/8, 8/6, 9/10, 10/11, 10/12, 11/14, 12/15, 13/10, 14/16, 16/13	16	1/9, 15/7	2

Table 6.15 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) and Node Unit Cost for mesh topology network

It is clear that the minimum total fiber links in this illustration is 16 in total as there are 16 nodes in the two networks. When IBC < CIBC, 8 IC are being used and operating fiber links remain to be 8. As IBC increases, the number of interconnection links used reduces eventually to a minimum of two. The operational fiber links remains to be a minimum of 14. It is also noted when node degree is considered, CIBC reduces from 1500 to 800-1000. More accurate CIBC can actually be identified.

Here we will try to derive the exact solution of CIBC. In Table 6.14, total operating cost after merger is g. When IBC is low, the number of OFL is 8 and IC is also 8 (except for Case 1 and 2 where 10 IC are used because flow cost savings are greater than IC cost) with a total of 16 fiber links used. When IBC is high, the number of OFL is 14 and IC is 2, again with a total of 16 fiber links used. The total node cost $b\times2\times(d+f) = b\times2\times16$ remains constant for all IBC. f = total fiber links used (i.e.16) – d is the number of OFL. The total OFL operating cost, $1000\times d$, + the interconnection build and operating cost, $f\times(a+100)$, becomes $1000\times d+(16-d)\times(a+100) = 16\times(a+100)+d\times[1000-(a+100)]$. When $a+100 < 1000$, d shall be as small as possible to minimize total cost. Therefore, the number of OFL shall be 8, and subsequently IC shall be 8, to be able to provide full connectivity of the merged network. When $a+100 > 1000$, d shall be as large as possible. Since the minimum number of IC is 2, the number of OFL shall be 14. When $a+100 = 1000$, a is the

CIBC i.e. CIBC occurs at when IBC + IC operating cost = OFL operating cost. Thus, we can derive the exact solution of CIBC as

$$\text{CIBC} = \text{OFL operating cost} - \text{IC operating cost} \quad (11)$$

After CIBC is identified, network planner can conclude that two interconnection links are required for IBC > CIBC with 14 OFL. The number of the two interconnection links can be derived from the analytical results of section 5.2.3. If IBC is less than CIBC, then 8 OFL and 8 IC will be required.

In the section, the model is extended in the objective function to take into account of node degree. Node degree analysis results are also in line with previous analytical and analysis results in Table 4.7 and 4.8 in Section 4.2. The model becomes more accurate to reflect the real situation when the effect of the node cost with respect to node degree is taken into account in the objective function of the model. With the addition of the node degree depended cost, it is found that an exact solution of CIBC can be obtained which is given by (the OFL operating cost – the IC operating cost).

6.3.2 Dual-ring topology

The revised model that takes into the consideration of node degree is also tested for the dual-ring topology as in Figure 3.1. The results are shown in Table 6.16 and 6.17 for information.

Case	IBC	Node Degree cost n_i	No. of OFL Required		Total Operating Cost before Merging	No of IC	Total Operating Cost after Merging	% of Cost Saved (%)
			Before Merging	After Merging				
	a	b	c	d	e = c×1000 + b×2×c	F	g = b×2×(d+f) + 1000×d + f×(a+100)	h=(e-g)/e
1	1	100	36	9	43200	8	13208	69.43
2	1	1000	36	9	108000	8	43808	59.44
3	1000	100	36	14	43200	2	19400	55.09
4	1000	1000	36	14	108000	2	48200	55.37

Table 6.16 Optimal Cost vs. Interconnection Build Cost (IBC)

and Node Unit Cost for dual-ring topology network

OFL: Operational Fiber Link; IC: Interconnection Link; IBC: Interconnection Build Cost

Similar results in fiber saving can be obtained with the revised model. In comparison with the 72.75% saving in the results of Table 3.1 when IBC is 1, in which flow cost is included; there is a small discrepancy in the percentage of fiber saving due to the increase in total operation cost when taken into account of node degree cost. (69.43% and 59.44% fiber links saving are provided to the operator for Case 1 and 2). Similar results for Case 3 and 4 are achieved.

Case /link	Node Degree Cost (n_i)	IBC	Operational Fiber Links	No. of OFL	Interconnection Links	No. of IC
1	100	1	1/2,3/5,8/9,12/6,14/15, 17/13,17/20,18/17,21/24	9	2/14,5/17,6/18,9/21, 13/1,15/3,20/8,24/12	8
2	1000	1	2/1,5/3,6/12,9/8,13/17, 15/14,17/18,20/17,24/21	9	1/13,3/15,8/20,12/24, 14/2,17/5,18/6,21/9	8

3	100	1000	1/2,2/3,3/5,5/6,6/12,9/8,12/9, 14/13,15/14,17/15,18/17, 20/21,21/24,24/18	14	8/20,13/1	2
4	1000	1000	1/5,2/1,3/2,5/8,8/9,9/12,12/6, 13/14,14/15,17/13,18/24, 20/14,21/20,24/21	14	6/18,15/3	2

Table 6.17 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) and Node Degree Cost for dual-ring topology Network

Table 6.17 depicts the optimal OFL and IC vs. IBC and node degree cost. It is shown that there are a total of 17 OFL + IC when IBC =1; and 16 OFL + IC when IBC = 1000. This is the same as in Table 4.1 for the dual-ring network.

6.4 Flow Cost

Flow cost has an effect on the number of OFL and IC and optimal cost. The effect of increase in flow cost and varying the flow cost are being examined.

6.4.1 Increase of flow cost

We had previously examined the cases with flow cost equal to 1. We now examine when flow cost is 6 and study its effect to the number of OFL and IC and optimal cost. The results are shown in Table 6.18 and 6.19.

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No. of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)=(e)-(f)	(h)	(i)=(h)x[(a)+100]	(j)=(g)-(i)	(k)=(j)/(e)
1	1	15413	36	10	36000	10000	26000	14	1414	24586	68.29%
2	800	20908	36	11	36000	11000	25000	6	5400	19600	54.44%
3	1000	22039	36	12	36000	12000	24000	5	5500	18500	51.39%
4	1100	22145	36	14	36000	14000	22000	3	3600	18400	51.11%
5	1200	22452	36	14	36000	14000	22000	2	2600	19400	53.88%
6	1300	22933	36	14	36000	14000	22000	2	2800	19200	53.33%
7	1500	23460	36	14	36000	14000	22000	2	3200	18800	52.22%
8	4000	27397	36	14	36000	14000	22000	2	8200	13800	38.33%

Table 6.18 Optimal Cost Objective Function vs. Interconnection Build Cost for dual-ring topology with flow cost = 6.

OFL: Operational Fiber Link; IC: Interconnection Link

When flow cost is 6, CIBC occurs at a higher IBC value than when flow cost is 1. Optimal cost also increases as flow cost increases. Less saving can be achieved because of the higher flow cost. After CIBC, the percentage of saving remains the same despite the change in flow cost. The number of IC remains to be two. The total number of OFL and IC remains to be the same. Flow cost does have an effect to the different number of OFL and IC in Case 2 to 4. Computation takes much longer than the lower flow cost case.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	1/4, 2/1, 4/3, 4/5, 5/7, 6/4, 7/8, 8/6, 11/10, 12/13	10	1/9, 3/11, 4/12, 5/13, , 6/14, 7/15, 8/16, 9/1, 10/2, 12/4, 13/5, 14/6, 16/8, 15/7	14	14
2	800	1/2, 3/4, 4/1, 4/5, 5/4, 7/8, 8/7, 10/9, 12/11, 13/15, 16/14	11	2/10, 5/13, 8/16, 11/3, 14/6, 15/7	6	4800
3	1000	2/1, 4/3, 4/5, 6/8, 8/7, 7/5, 9/12, 11/10, 13/15, 14/12, 16/14, 15/16	12	1/9, 3/11, 5/13, 10/2, 12/4	5	5000
4	1100	2/1, 3/2, 4/3, 4/6, 6/8, 8/7, 7/5, 9/10, 10/11, 11/12, 13/15, 14/12, 16/14, 15/16	14	1/9, 5/13, 12/4	3	3300
5	1200	2/1, 3/2, 4/3, 5/4, 6/8, 8/7, 7/5, 8/10, 10/11, 11/12, 12/13, 13/15, 16/14, 15/16	14	1/9, 14/6	2	2400
6	1300	2/1, 3/2, 4/3, 5/4, 6/8, 8/7, 7/5, 9/10, 10/11, 11/12, 12/13,13/15,16/14, 15/16	14	1/9, 14/6	2	2600
7	1500	2/1, 3/2, 4/3, 5/7, 6/4, 8/6, 7/8, 9/10, 10/11, 11/12, 12/14, 14/16, 16/15, 15/13	14	1/9, 13/5	2	3000

8	4000	1/2, 2/3, 3/4, 4/5, 5/7, 8/6, 7/8, 10/9, 11/10, 12/11, 13/12, 14/16, 16/15, 15/13	14	9/1, 6/14	2	8000

Table 6.19 Operational Fiber Link (OFL) and Interconnection Link (IC) location vs. Interconnection Build Cost (IBC) for dual-ring topology (Fig. 3.1)

with flow cost = 6

The total number of OFL and IC in Case 2 to 4 remains to be 17. However, the required number of IC varies with the number of OFL required. After CIBC, the number of OFL remains to be 14, and the number of IC again remains to be 2.

6.4.2 Varying flow cost

We now examine the case when the flow cost is varied to see its effect to OFL and IC.

Case	Flow cost	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No. of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	18875	36	14	36000	14000	22000	2	2200	19800	55.00%
2	10	24445	36	16	36000	16000	20000	3	3300	16700	46.38%
3	30	35660	36	14	36000	14000	22000	5	5500	16500	45.83%
4	50	46431	36	18	36000	18000	18000	6	6600	11400	31.66%

Table 6.20 Optimal Cost Objective Function vs. Flow Cost for dual-ring topology (Fig. 3.1)

when IBC = 1000.

OFL: Operational Fiber Link; IC: Interconnection Link

As flow cost increases, the total number of OFL and IC increases. Optimal cost also increases along with the increase in flow cost. Computation time deceases since there are fewer paths for traffic to route through. In Case 2 and 3, flow cost does have an effect on the mix of the OFL and IC.

Case	Flow Cost	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	1/4, 2/1, 3/2, 9/10, 12/9, 10/11, 4/6, 14/12, 6/8, 16/14, 8/7, 15/16, 7/5, 13/15	14	5/13, 11/3	2	2000
2	10	1/4, 2/1, 4/3, 4/5, 4/6, 6/8, 7/5, 8/7, 9/10, 12/9, 12/11, 13/12, 13/15, 14/12, 15/16, 16/14	16	5/13, 10/2, 11/3	3	3000
3	30	1/4, 2/3, 3/4, 4/6, 5/4, 6/8, 7/5, 11/10, 12/11, 12/9, 12/13, 13/15, 14/12, 16/14	14	4/12, 8/16, 9/1, 10/2,15/7	5	5000
4	50	1/2, 3/4, 4/1, 4/5, 4/6, 5/4, 6/8, 7/5, 8/7, 9/12, 10/9, 12/11, 12/13, 13/12, 13/15, 14/12, 15/16, 16/14	18	1/9, 2/10, 5/13, 6/14, 11/3, 12/4	6	6000

Table 6.21Operational Fiber Link (OFL) and Interconnection Link (IC) location vs. Flow Cost for dual-ring topology (Fig. 3.1) when IBC = 1000

In Case 2 to 4, at IBC= 1000, the number of IC is greater than two, thus CIBC will occur at a higher value of IBC. In Case 1, CIBC has been achieved and the number of IC is two with location at one node away from the articulation node. Further studies can be explored on the issue of flow cost vs. IBC.

6.5 Protection of the optimal network

Protection to network is an important issue for network planners. The most optimal cost can be determined and using the model presented can identify the number of interconnection links and their location. The question remains is how one can protect this optimal solution.

Single failure of either a fiber link or a node is the most common failure scenario. It is possible to have multiple links failure with a smaller probability. Multiple links failure occurs when the first link fails. The recovery from link failure can be in milliseconds, like in SONET/SDH networks, but the failed physical link may take hours or days to be repaired. This probability can be calculated based upon average repair time and failure rate [51]. The second situation is that two fiber links may be physically routed together and they are cut together, and therefore leading to the failure of both links.

Protection is generally done by providing two paths for transporting traffic. A primary path and a back up path are being provided. The efficient utilization of back up capacity is more important in order to save cost. Backup path can share the wavelengths on their common links. It is normal that triple of the amount of spare capacity is required to offer dual-failure restoration for a network. Other approaches such as shared-mesh protection or backup multiplexing can lower this requirement.

L_{min} is the minimum fiber links required in the optimal solution as illustrated in the previous section. In order to provide 1 + 1 protection for any operational fiber link failure, 2 L_{min} is required. The working L_{min} + the backup L_{min} can protect any single failure of L_{min}. For the dual-ring topology in Fig. 3.1, when IBC is small, 9 OFL are required with no protection is employed. If single failure protection is required, 18 OFL, by doubling each span, will be needed. The above protection assumes IC will not be cut. In the event that IC may fail, then 2 (L_{min} + the number of IC) are required for 1 + 1 protection.

For double link failure at any places, it does not necessary need two times of the total operational fiber links for protecting single failure. The required operational fiber links can be 3 L_{min} for dual-ring, circle and mesh topology. This is topology dependent. As shown in Figure 6.8 for the dual-ring topology, when double failure occurs at links (1/4 and 4/6), traffic can route to node 4 through IC from node 12. When links (12/14 and 14/12) fail, traffic can still route to node 12 and 14. This cannot apply to bus and tree topology. Since these topologies only have a maximum of 2 L_{min} fiber links (i.e. 28 links = total number of OFL before merging), only single failure protection can be supported. Further studies and investigation in this area can be carried out for different failure situations.

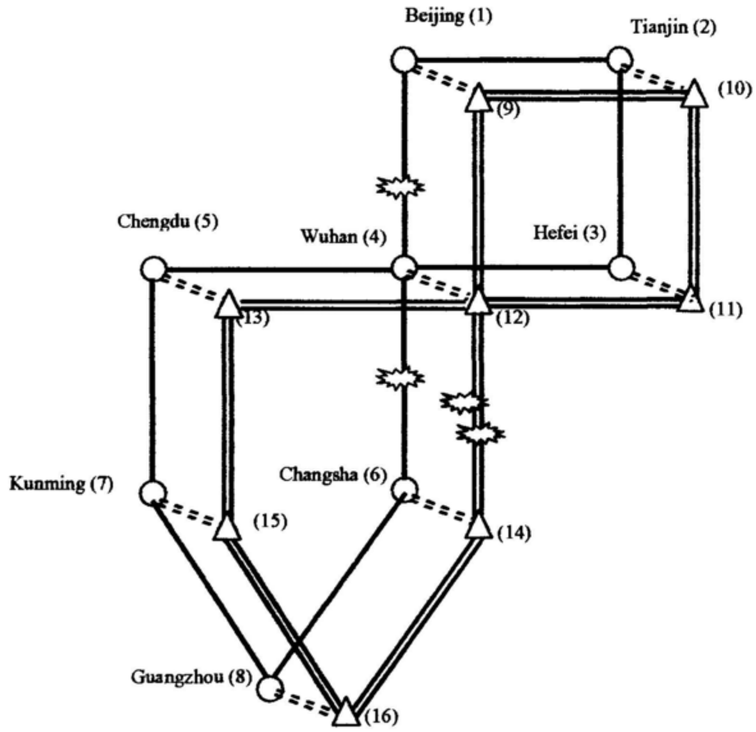

Figure 6.8 Example for double failure protection for a dual-ring topology

○& △: nodes on network A & B

6.6 Application to non-identical networks

In the situation of merging two non-identical networks, our model caters for this application. In a non-identical network situation, not all of the nodes are co-located nodes. These nodes can not be interconnected.

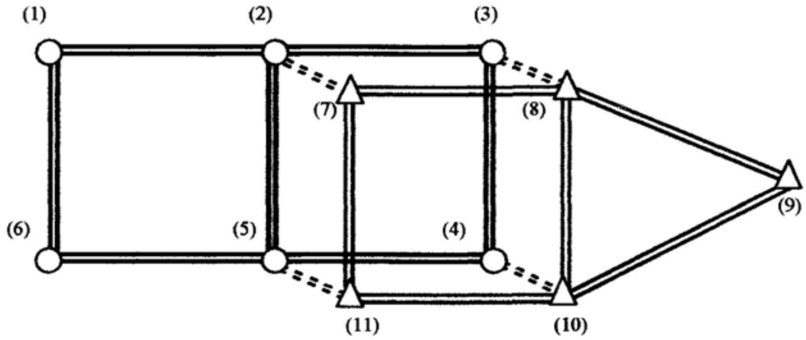

Figure 6.9 Two non-identical networks with 11 nodes / 26 OFL

○& △: nodes on network A & B.

Fig. 6.9 illustrates a 6-node network and another 5-node network with only 4 nodes being permitted to be interconnected. This therefore becomes a large network of 11 nodes with 26 fiber links and 8 IC. Further case studies can be carried out accordingly as shown in Table 6.22 and 6.23.

Case	IBC	Optimal Cost	No. of OFL Required: Before Merging	No. of OFL Required: After Merging	Operating Cost of OFL: Before Merging	Operating Cost of OFL: After Merging	OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
	(a)	(b)	(c)	(d)	(e)	(f)	(g)=(e)-(f)	(h)	(i)=(h)x[(a)+100]	(j)=(g)-(i)	(k)=(j)/(e)
1	1	9016	26	7	26000	7000	19000	6	606	18394	70.75%

2	400	11406	26	8	26000	8000	18000	4	2000	16000	61.54%
3	800	12263	26	9	26000	9000	17000	2	1800	15200	58.46%
4	900	12463	26	9	26000	9000	17000	2	2000	15000	57.69%
5	1000	12663	26	9	26000	9000	17000	2	2200	14900	56.92%
6	2000	14663	26	9	26000	9000	17000	2	4200	12800	49.23%
7	4000	18663	26	9	26000	9000	17000	2	8200	8800	33.85%

Table 6.22 Optimal Cost vs. Interconnection Build Cost (IBC) for non-identical networks

OFL: Operational Fiber Link; IC: Interconnection Link

Table 6.22 shows that CIBC occurs when IBC is 800. The parameters used are the same as Table 3.1 except there are a total of 110 commodities. Again after CIBC, only two IC are required. Thus it is shown that the model can apply to the merger of non-identical networks.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	1/2,2/3,5/6,6/1,8/9,9/10,10/11	7	4/10,10/4,11/5, 7/2,2/7,3/8	6	6
2	400	1/6,2/1,3/2,5/4,6/5,9/8,10/9,11/7	8	4/10,5/11,7/2,8/3	4	1600
3	800	1/2,3/4,4/5,5/6,6/1,7/11,9/8,10/9,11/10	9	2/7,8/3	2	1600
4	900	1/6,2/1,4/3,5/4,6/5,8/9,9/10,10/11,11/7	9	3/8,7/2	2	1800
5	1000	1/2,2/3,3/4,5/6,6/1,7/11,8/7,9/8,10/9	9	4/10,11/5	2	2000
6	2000	1/6,2/1,3/2,4/3,6/5,7/8,8/9,9/10,11/7	9	10/4,5/11	2	4000
7	4000	1/6,2/1,4/3,5/4,6/5,8/9,9/10,10/11,11/7	9	3/8,7/2	2	8000

Table 6.23 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC)

vs. Interconnection Build Cost (IBC) for non-identical networks

As noted in Table 6.23, all overlapping and non-overlapping fiber links are being optimized. After CIBC, cost savings decreases as IBC increases. The amount of OFL savings remain the same. A minimum of 9 OFL are required and again only two IC are required after CIBC. The case analysis finds a Hamiltonian cycle for the merged network. As there are totally 11 nodes in the two networks, the required number of OFL + IC will be 11. One of the optimal results is shown in Fig. 6.10 when IBC is 800.

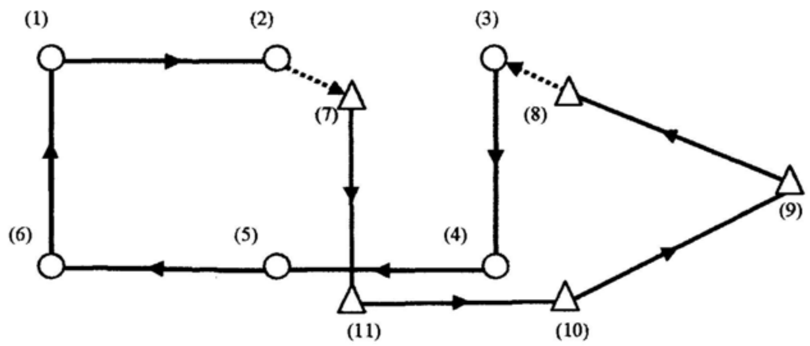

Figure 6.10 Two non-identical networks after merging at CIBC with 11 nodes/26 links (IBC = 800 of Table 6.22 & 6.23); solid line: operational fiber link; dotted line: Interconnection Link; ○ & △: node on network A & B.

The merger of the NSFNET network and the Abilene network

We also simulate the merger of the NSFNET network and the Abilene network to observe the effect of the merging in a real situation. The combined network topology is shown in Fig. 6.11 with a total of 24 nodes and 60 links for the combined network. There are 10 available co-located nodes. The results are shown in Table 6.24 and 6.25.

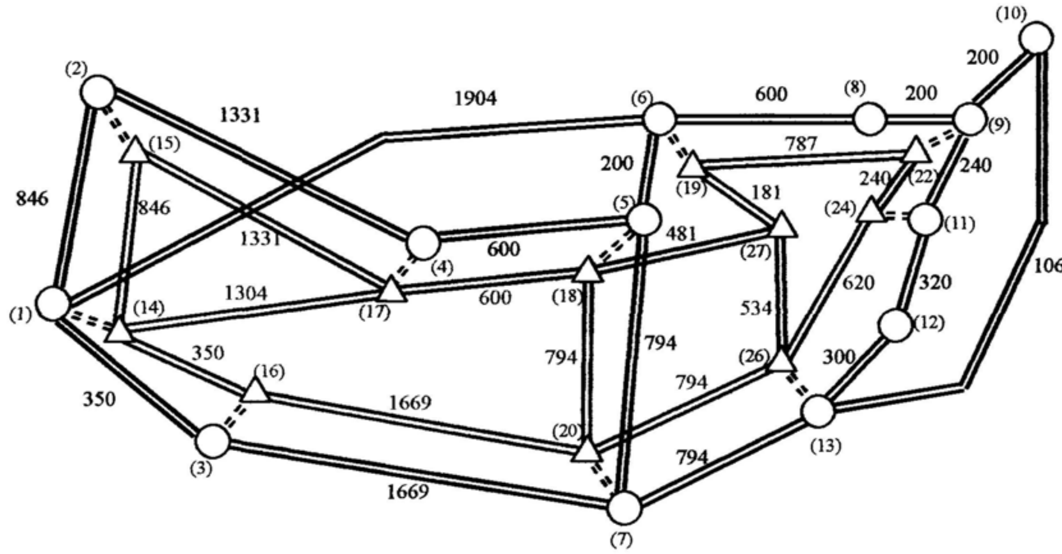

Figure 6.11 A combined NSFNET and Abilene non-identical network with a total of 24 nodes/60 links and 10 IC locations; solid line: operational fiber link; dotted line: Interconnection Link; ○ & △: node on NSFNET network & Abilene network respectively.

Case	IBC	Optimal Cost	No. of OFL Required		Operating Cost of OFL		OFL Cost Saved	No of IC	Total IBC + IC Operating Cost	Net Cost Saving	% of Cost Saved / Fiber Operating Cost before Merging
			Before Merging	After Merging	Before Merging	After Merging					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)= (e)-(f)	(h)	(i)= (h)x[(a)+ 100]	(j)= (g)-(i)	(k)=(j)/(e)
1	1	18879	60	16	60000	16000	44000	12	1212	42788	71.31%
2	1000	28213	60	23	60000	23000	37000	2	2200	34800	58.00%
3	2000	29357	60	23	60000	23000	37000	2	4200	32800	54.66%

Table 6.24 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for combined NSFNET/Abilene Network

OFL: Operational Fiber Link; IC: Interconnection Link

Table 6.24 shows that optimal cost, % of cost saving, and computation time reduce compared with the NSFNET network results. There are fewer nodes in the combined network (24) than the two identical NSFNET networks (26). In addition, there are fewer available IC locations in the combined network (10) than the NSFNET network (13). The number of IC again reduces to two when IBC=1000 and OFL reduces from 60 to 23 as shown in Fig. 6.12.

Case	IBC	OFL Required	No. of OFL Required	IC Locations	No. of IC Required	Total IBC
1	1	3/7, 4/2, 5/18, 8/6, 9/8, 10/9, 11/12, 12/13, 13/10, 14/16, 15/14, 18/17, 19/27, 20/26, 22/24, 27/18	16	2/15, 1/14, 7/20, 9/22, 6/19, 14/1, 16/3, 17/4, 18/5, 22/9, 24/11, 26/13	12	12
2	1000	1/2, 2/4, 3/1, 4/5, 5/6, 6/8, 7/3, 8/9,9/10, 10/13, 12/11, 13/12, 14/16, 15/14, 16/20, 17/15, 18/17, 19/27, 22/19, 24/22, 24/26, 26/24, 27/18	23	11/24, 20/7	2	2000
3	2000	1/2, 2/4, 3/1, 5/7, 6/5, 7/3, 8/6, 9/8, 10/9, 11/12, 12/13, 13/10, 14/15, 15/17, 16/14, 17/18, 18/27, 19/22, 20/16, 22/24, 27/19, 27/26, 26/20	23	4/17, 24/11	2	4000

Table 6.25 Optimal Operational Fiber Link (OFL) and Interconnection Link (IC) vs. Interconnection Build Cost (IBC) for combined NSFNET/Abilene Network

These results show that the model can apply to the merger of two non-identical real networks.

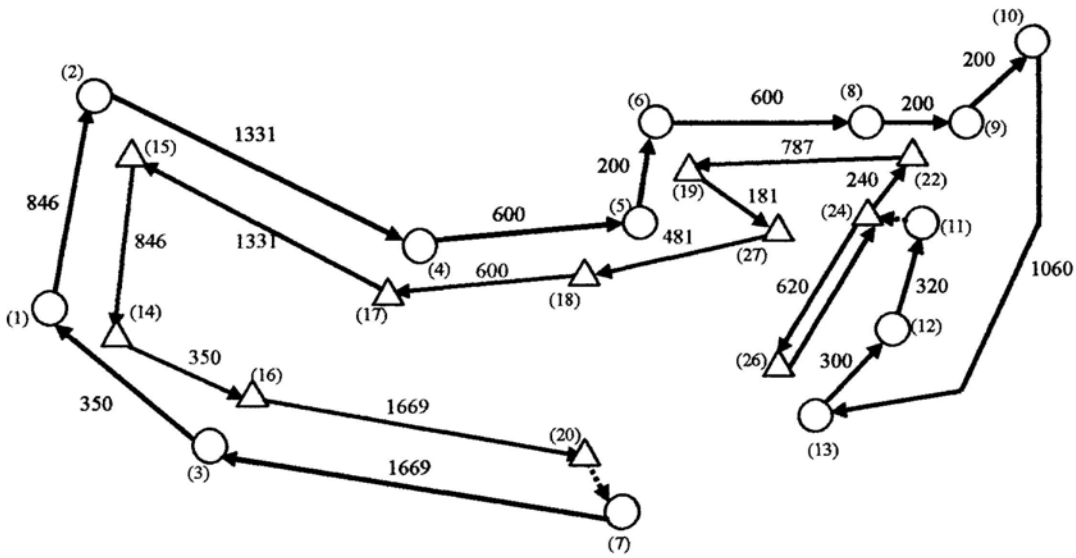

Figure 6.12 A resultant merged NSFNET and Abilene non-identical network with a total of 24 nodes/23 links and 2 IC when IBC = 1000;

solid line: operational fiber link; dotted line: Interconnection Link;

○ & △: node on NSFNET network & Abilene network respectively.

6.7 Summary

The extension of the model was discussed and the model is flexible. The capacity of the model was illustrated through the addition of the number of nodes to the dual-ring topology network. Computation time increases as the number of nodes increases. However, similar results are obtained. The investigation of the Abilene network and the NSFNET network indicates that ultimately only two interconnection links are required for interconnection. It also indicates that the model can apply to different number of node configuration and topologies. Scalability of the model is achieved. The China network was also illustrated to show that with the use of real data for IBC, node capacity, node cost, and fiber operating cost, the model could still be used for the optimization. Commodity number and flow cost were the variables for the analysis.

The relationship of node degree to node cost was also incorporated into the objective function to more accurately reflect the real scenario. Case analysis results indicate that IBC and node cost are both significant factors in the analysis of the minimum cost after network consolidation. In addition, it is worth noting that an exact solution of CIBC can be derived in this case.

Protection of the optimal network was discussed. The minimum number of fiber links required is 2 L_{min} for 1 + 1 protection. Other path protection solution is also referred.

The model has proven to be viable and flexible. The model can be used for the merger of both identical and non-identical networks. Optimization of merging two identical networks has been illustrated already. As for two non-identical networks, the fiber links that stand on their own must be connected in order to maintain connectivity to all nodes. An example of the optimization of the merger of two non-identical networks was shown successfully. It is therefore concluded that optimal solution in terms of cost, number of interconnection links and their locations can be identified.

Chapter 7

Contributions and future work

7.1 Contributions

This thesis studies the optimization of the operational fiber links and the interconnection links for the merger of two optical networks. Adding interconnection fiber links between co-located nodes of networks can merge networks. Operational fiber links can be saved from this merger of two networks.

A model has been developed and by using CPLEX program, the optimal cost for the network, the fiber links saved, and the interconnection locations can be identified. The effect of interconnection build cost to the number of interconnection links, the location of interconnection links, and the fiber saved are analyzed. The model supports the investigation of merging two individual networks with interconnection links between co-located nodes. The case analysis can provide the network planners with the optimal number of operational fiber links and their locations that will give the optimal cost for the operator.

Both the analytical results and case analysis results show that the IBC has direct impact on the number of interconnection links and fiber links saved. When IBC is low, more interconnection links will be used. Once the CIBC is determined, only two interconnection links are required for the optimal solution for any given IBC which is greater than the CIBC. The total number of operational fiber links used will depend on the number of fiber links that will form a Hamiltonian cycle or path for the merged network and maintain connectivity to all nodes. No further saving in fiber can be achieved after CIBC is reached.

When interconnection links are equal to two, which is the minimum number required, one interconnection link will go from one network to another and the other interconnection link will go in reverse. In most of the topologies discussed, a Hamiltonian path can be found. If Hamiltonian path is not available, then a path that contains a maximum number of directly connected articulation nodes in different groupings needs to be found. Otherwise, case analysis will need to be used to find the optimal interconnection locations for the concerned topology.

An analytical formula was also presented for the minimum number of fiber links required when all co-located nodes are interconnected, corresponding to the case when interconnection build cost is negligible.

Extension of the model was discussed. Firstly, the expandability of the number of nodes was simulated, and then three real networks situations were investigated. The issue of node connectivity and node cost was incorporated into the model for case studies. Flow cost can also vary in the model for analysis purpose. It has been shown that the model can be extended for more comprehensive study and the analysis result agree well with the analytical results.

Protection issue for the merger of networks was discussed. Minimum fiber links required with protection were also discussed.

The merger of two optical networks will definitely provide fiber link savings to the operator. In all case studies, substantial amount of fiber links can be saved depending upon its topology. It ranges from 83.91% saving for the mesh topology to 48.92% for the bus topology while IBC is negligible (= 1). The effect of flow cost becomes significant when IBC is low. It may introduce additional IC to achieve saving in flow cost. This thesis has provided the technique for the network planners to optimize the use of fiber links.

Conclusions can be drawn from the investigations within the thesis. For the consolidation of two identical networks, we can derive the following. (i) The number of IC = 2 after CIBC. (ii) The optimal number of operational fiber links and interconnection links can be identified for various topologies. (iii) The optimal location of the interconnection links and operational fiber links can be identified. (iv) When a Hamiltonian cycle can be found, IBC is low and all co-located nodes are interconnected, the number of OFL after merger is equal to the number of nodes of one network. When IBC is high, there shall be only two IC. The number of OFL and IC after the merger is equal to the total number of nodes of the two networks. (v) The percentage of cost saving depends on the topologies, node connectivity, and the size of the network. For instance, mesh shows more reduction than tree or bus. (vi) The proposed model is flexible and can be extended and used in a real situation and non-identical networks.

Network planners can easily use these results to arrive at an optimal design network for a merger situation of two existing networks.

7.2 Recommendations for future work

Further analysis and studies can be carried out on the interconnection locations with respect to different and non-uniform traffic demand flow patterns. Traffic pattern can be predicted based upon population density, customer behaviors, and business centers etc. Demand model can be worked out for more accurate identification of the interconnection locations. We assumed no constraint on the equipment capacity in our study. This can be refined to reflect the real situation for load balancing. Random traffic pattern has been used in one preliminary study. However, there was no conclusive result derived. The model does support the analysis of random traffic. More studies can be carried out using the aforementioned demand model in the future work. Capacity backup for protection can also be incorporated into this demand model. The amount of cross traffic between two networks may have an influence on the number of interconnection and equipment deployment for the node etc. This can also be studied more extensively.

Some flow cost analyses were carried out but further analysis can be carried out on the effect of flow cost on interconnection fiber link especially when IBC is low. This issue affects the optimal cost and the location of interconnection links. In this thesis, parameters values were fixed in order to isolate the effect and to obtain some insights of the characteristics in the optimization of merging two networks.

The protection issue of the network optimization can be further studied. This will of course lead to less saving in OFL. Other network management issues such as network monitoring, early detection, and fault recovery techniques will have bearings on the number of operational fiber links and will affect the ultimate fiber links cost savings to the operator.

The effect of interoperability of the two networks with equipments from different vendors may affect the interconnection build cost. Since equipment may not be compatible with each other. Additional equipment may be needed for interoperability to the merged system. This may give different results for the ultimate number of OFL and IC required.

These studies will further enhance network planners' appreciation and understanding to the importance of resources optimization in the merger of two optical networks.

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