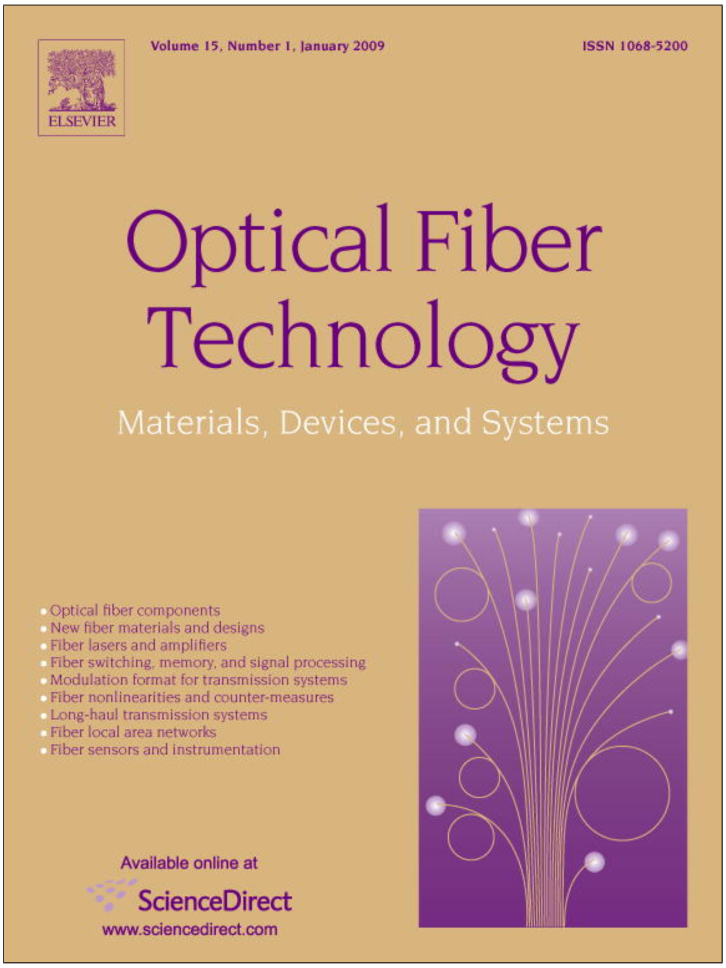
Volume 15, Number 1, January 2009
ISSN 1068-5200
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Optical Fiber Technology 15 (2009) 57–64

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Optical Fiber Technology

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Optimization of operational fiber links and interconnections for the merger of two networks

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ARTICLE INFO

Article history:
Received 11 November 2007
Revised 19 March 2008
Available online 23 May 2008

Keywords:
Network merging
Network optimization
Resource allocation
Hamiltonian path
Network topology

ABSTRACT

Multiple telecommunication networks create redundancy in fiber resources. Merging two networks can achieve savings in redundant fiber links. In this paper, we investigate the merge of two networks by adding fiber interconnections. A simulation model is developed for the optimization. The overall costs for various topologies are optimized with respect to different interconnection build costs. We show, by simulation and analytical results, that through the merger of two networks, it reduces more than 50% of operational fiber links. We are able to provide routing between any two nodes in the two networks. In all cases after critical interconnection build cost, only two interconnections are needed. The optimization is performed 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 in different groupings. The proposed simulation model finds the optimal interconnection locations for these topologies.

1. Introduction

Telecommunication networks have been carrying voice traffic for decades. Carriers have constructed many fiber optic networks with the growth of data traffic. Deregulation and open competition enhance pressure on carriers to compete based upon quality of service (QoS), capacity and operating margin. Overcapacity is the result of over expansion of network resources. Different carriers have constructed networks with similar geographical coverage in more profitable areas. This may result in insufficient demand in sustaining multiple networks [1–3].

In a competitive market, carriers 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% 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 carriers 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. Optimization involves finding the optimal solution for the merger of two networks, based on a number of constraints.

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 paper, we present a simulation 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 paper are as follows. (a) A model for the simulation of optimizing the merger of two networks is developed. (b) The CPLEX program is used for the optimization. Under various

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1068-5200/$ – see front matter
doi:10.1016/j.yofte.2008.04.005

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 links and interconnection links. (e) From these investigation, we can show significant improvements in fiber link saving. Therefore cost saving and efficiency to the operator are possible with the merger of two networks. The results have not taken into account of interoperability of the two networks. Depending on the degree of the interoperability, additional cost and constraints may incur in the optimization. For instance, we may need to retain two network management systems and add additional equipment for interfacing at the interconnections.

The paper is organized as follows: In Section 2 we describe the optimization model, including constraints. Section 3 describes the real China network in dual-ring topology with assumptions and results. Section 4 will have a brief description of the different topologies used, namely circle, tree, bus, and mesh. These topologies will be compared with the dual-ring topology and the results of our findings are given under different topologies. Section 5 concludes the paper.

2. Optimization model

In this section, we develop a minimum cost model for two co-existing networks and find the optimal interconnection nodes and fiber links to be saved. We will discuss the model and constraints.

Mathematical programming methods are commonly used to formulate the spare capacity planning problem for link and path [2,10]. 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 [11,12].

In order to merge two co-existing networks, we need to build fiber interconnection links that connect network nodes located in the same city. 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.

In our previous paper [2], a preliminary model was first presented 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). This paper 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 [13]. The objective function is the overall cost C:

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

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 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 cost of fiber link from node i to node j where $1 \leqslant i \leqslant N$ and $1 \leqslant j \leqslant N$. 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.

The constraints are given in the following.

$$\sum_{(i,j) \in A} x_{ij}^k - \sum_{(i,j) \in A} x_{ji}^k = \begin{cases} v^k, & \text{if } i = s^k, \\ -v^k, & \text{if } i = d^k, \\ 0, & \text{otherwise,} \end{cases} \quad \forall i, j \in V,\ 1 \leqslant k \leqslant K. \tag{2}$$

Equation (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 $1 \leqslant k \leqslant K$. 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 cannot be larger than the volume of commodity k [2,10,13].

$$\sum_{1 \leqslant k \leqslant K} x_{ij}^k \leqslant u_{ij} y_{ij}, \quad \forall (i, j) \in A. \tag{3}$$

Equation (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) [13].

$$\sum_{(i,j) \in A} \left(x_{ij}^k + x_{ji}^k\right) \leqslant q_i z_i, \quad \forall i \in V,\ 1 \leqslant k \leqslant K. \tag{4}$$

Equation (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.

$$x_{ij}^k \geqslant 0, \quad \forall (i, j) \in A,\ 1 \leqslant k \leqslant K. \tag{5}$$

Equation (5) states that flow is non-negative.

$$y_{ij} \leqslant a_{ij}, \quad \forall (i, j) \in A. \tag{6}$$

Equation (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.

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

$$z_i = \{0, 1\}, \quad \forall i \in V. \tag{8}$$

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

We also need to examine different topologies, since routing configuration and backbone topology have significant implications on user performance and resource efficiency [14].

3. Real China dual-ring network

We first examined a dual-ring network, part of a real China network as shown in Fig. 1. It consists of two 8 nodes/36 links network with possible interconnection links at all the co-located nodes.

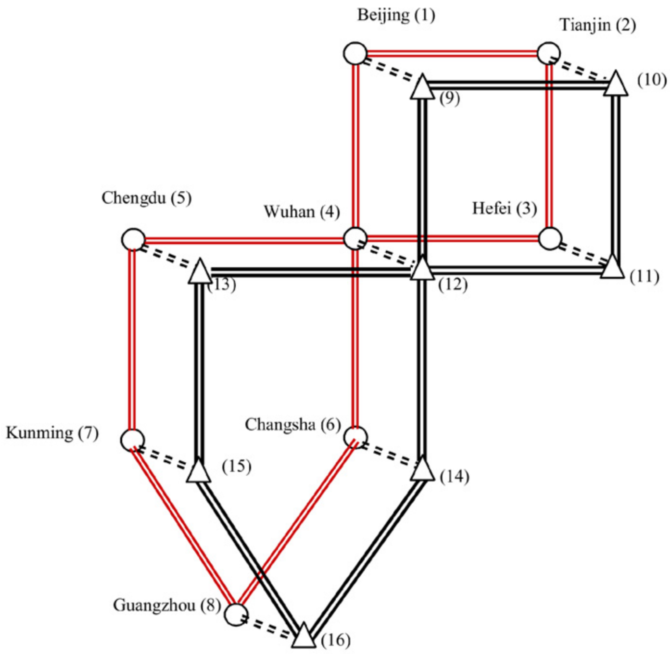

Fig. 1. Two dual-ring-topology networks with 16 nodes/36 links (○) and (△) nodes on networks A and B.

3.1. Basic assumptions for the dual-ring topology

In our model, some basic assumptions are made. Two networks with identical geographic coverage are considered. There are 16 nodes in total, with eight nodes in each network. We assume that no losses in nodes and fiber links will occur when commodities flow within the network [2]. We also assume that the distances of all co-located nodes are 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. 1 are the same, thus all interconnection build costs are 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. 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. Traffic demands vary, depending on user behavior, performance of network elements, and routing policies [14,15]. However, we assume the two existing networks have traffic flow in all nodes and they run from each node to every other node [16]. Therefore a total of 240 ($= 16 \times 15$) traffic commodities are used, each is assumed with a 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. We assume that the fiber operation cost is constant to study the effect of different topologies.

Node operating cost is also assumed to be uniform at a value of 100. 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 large value of 1000. Both fiber and equipment capacity are not of concern since equipment can be relocated from redundant nodes and therefore they pose no limitation to capacity. We have restriction on the usage of certain fiber links a_{ij}, depending

Table 1
Parameters for the merger of two networks and their values

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	1–20,000

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 we are merging two existing networks, we assume no build cost for existing fiber links. However, we will vary the build cost of the interconnection links in this study.

We have kept most of the parameters 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. Albeit a few assumptions have been made in this study, the model itself is quite flexible that it can accommodate various needs. For instance, non-uniform operating cost can be assigned to different nodes, instead of uniform operating cost for all nodes. Special attention to the assumptions made is needed when applying the results. We hereby summarize these parameters in Table 1 for reference.

3.2. Simulation results and findings for the dual-ring topology

Table 2 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. 1). IBC is chosen as a variable in the study as it 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. As the build cost increases, the optimal cost increases. When IBC is low, the number of required operational fiber links 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. Fiber operating cost saved minus the build cost and operating cost of interconnection links gives the net cost saving (column (j) in Table 2). The percentage of the cost saved with respect to the total fiber link operating cost can then be calculated (column (k) in Table 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. We also note that with IBC = 1, 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 3 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.

Table 3 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

Table 2
Interconnection build cost vs optimal cost objective function for dual-ring topology. OFL: operational fiber link; IC: interconnection link

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)[(a) + 100]	(j) = (g) − (i)	(k) = (j)/(e)
1	1	12,161	36	9	36,000	9000	27,000	8	808	26,192	72.75%
2	400	14,986	36	9	36,000	9000	27,000	8	4000	23,000	63.89%
3	600	16,561	36	9	36,000	9000	27,000	8	5600	21,400	59.44%
4	800	17,706	36	12	36,000	12,000	24,000	4	3600	20,400	56.67%
5	900	18,238	36	14	36,000	14,000	22,000	2	2000	20,000	55.55%
6	1000	18,875	36	14	36,000	14,000	22,000	2	2200	19,800	55.00%
7	2000	20,952	36	14	36,000	14,000	22,000	2	4200	17,800	49.44%
8	4000	24,503	36	14	36,000	14,000	22,000	2	8200	13,800	38.33%
9	6000	28,952	36	14	36,000	14,000	22,000	2	12,200	10,000	27.78%
10	8000	32,952	36	14	36,000	14,000	22,000	2	16,200	5800	16.11%
11	10,000	36,952	36	14	36,000	14,000	22,000	2	20,200	1800	5.00%
12	20,000	41,958	36	14	36,000	14,000	22,000	2	40,200	No saving	

Table 3
Interconnection build cost (IBC) vs operational fiber link (OFL) and interconnection link (IC) location for dual-ring topology

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	12,000
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	16,000
11	10,000	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	20,000
12	20,000	4/1, 1/2, 2/3, 8/7, 6/8, 7/5, 11/10, 5/4, 10/9, 9/12, 12/13, 16/14, 15/16, 13/15	14	3/11, 14/6	2	40,000

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. The interconnection locations will be discussed in Section 3.3. With the cost saving from Table 3 on fiber links saved and the extra cost for interconnection links, we can then calculate the net cost saving for a merged network as shown in Table 2. In all cases, a merged network will not result in saving when the saving in operating cost of fiber link are not able to cover high interconnection build cost, e.g., in Case 12.

3.3. Discussion on the result for the dual-ring topology

3.3.1. IBC vs number of interconnections and optimal cost

In Table 2, 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 2 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 increasing of interconnection links and the corresponding further saving in operating cost of fiber links. Interconnection links increase only when further saving in the operating cost of fiber links can offset the interconnection build cost.

3.3.2. Minimum of two interconnections and their locations

The number of interconnection links eventually reduces to a minimum value of two at certain interconnection build cost which is defined as the critical interconnection build cost (CIBC). Substantial savings only occur when IBC is smaller than CIBC as more interconnection links 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.

For the location of the two interconnection links when interconnection build cost is beyond CIBC, it is discovered that there is a Hamiltonian path that covers all the nodes in the dual-ring topology [17]. With two interconnection links and two Hamiltonian paths of the two identical dual-ring networks, a big Hamiltonian cycle connects all the 16 nodes with a minimum of 14 operational fiber links. One possible solution is shown in Fig. 2. For Case 5 of Tables 2 and 3 with IBC = 900, traffic flow will go in 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.

3.3.3. Analytical results for all interconnected case

We can also derive some analytical results of saving in fiber links with interconnection links 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 [18]. An equation that can be applied to all aforementioned network topologies to achieve maximum saving in fiber links is derived. We assume zero interconnection operating cost and all co-located nodes are interconnected.

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

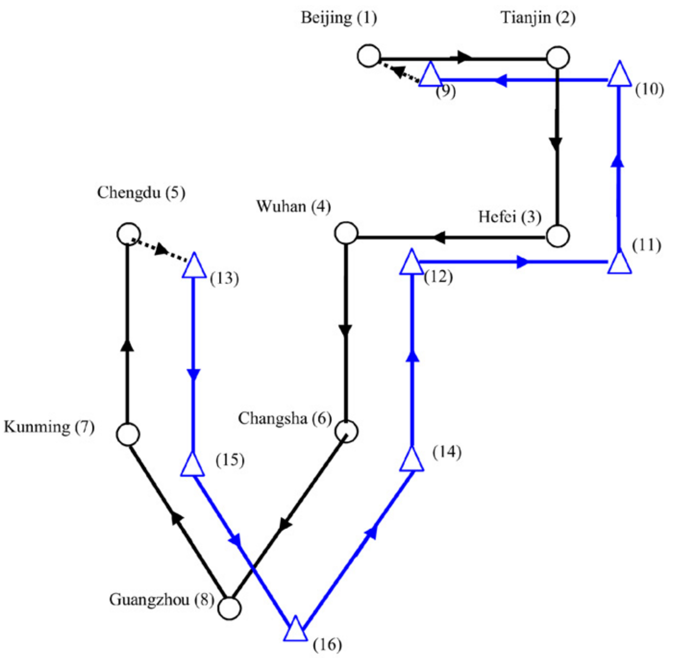

Fig. 2. Two dual-ring topology networks after merging at CIBC with 16 nodes/16 links (Case 5 of Table 2, IBC = 900); solid line: operational fiber link; dotted line: interconnection link; (○) and (△) nodes on networks A and B.

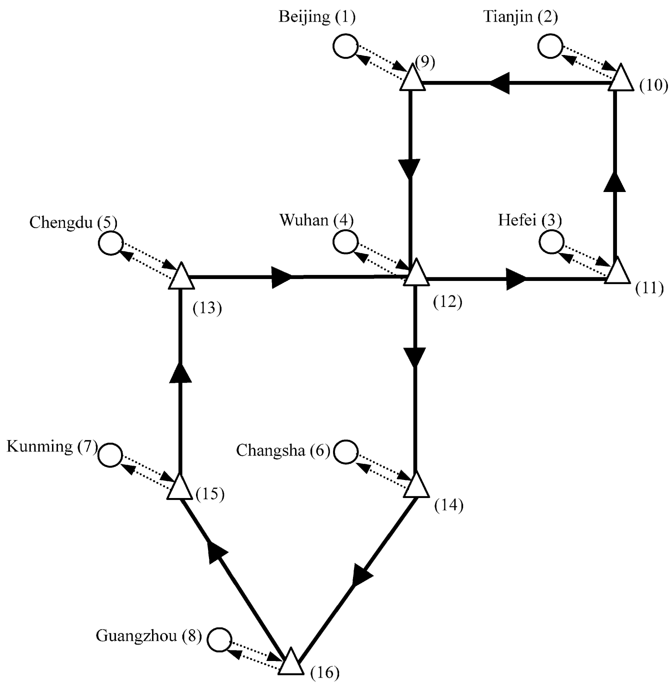

Fig. 3. Two dual-ring topology networks after merging with IBC = 0 with 16 nodes/25 links (○) and (△) nodes on networks A and B.

L_{min} is the minimum number of fiber links (OFL) required. B is the number of bridges in one network. A bridge is defined as the fiber link which, 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 shall first examine whether there is any bridge in the network. If so, the bridges shall be removed first before evaluating the number of articulation nodes.

In the case of the dual-ring topology, 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. 3. In terms of the number of interconnection links, this is different from case 1 in Table 2 (IBC = 1), which has only eight interconnection links. The above simulation results agree with the analytical results on the number of fiber links saved. We note that there is a minor discrepancy in cost saving compared with the simulation results. It is because simulation results include the build cost and operating cost of interconnection links.

4. Other topologies consideration

Four other topologies are used in the investigation, namely circle, tree, mesh, and bus as shown in Figs. 4–7. There are two types of fiber links, the operational (for intercity) and the interconnection links (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. Only one network of the two identical networks (network A and B) is shown in Figs. 4–7. Notation (i, j) represents co-located nodes with node i in network A and node j in network B. Interconnection links will only occur, if needed, in co-located nodes (i, j). 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.

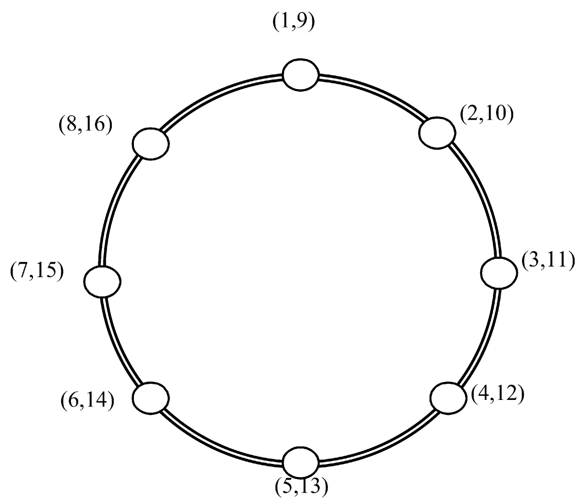

Fig. 4. Two circle-topology networks with 16 nodes/32 links Node (i, j) is node i in network A and node j in network B.

Five topologies are investigated and compared. In Fig. 1, the dual-ring topology actually is a reduced form of the real fiber network in China [2]. Figs. 4–7 are typical topologies for consideration. We fix the number of nodes to eight per network for all topologies to facilitate fair comparison amongst different 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.

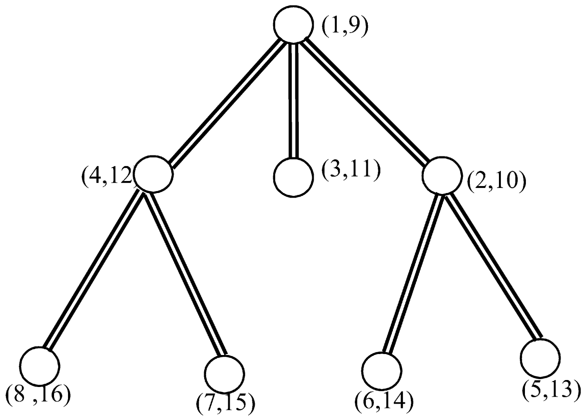

Fig. 5. Two tree-topology networks with 16 nodes/28 links Node (i, j) is node i in network A and node j in network B.

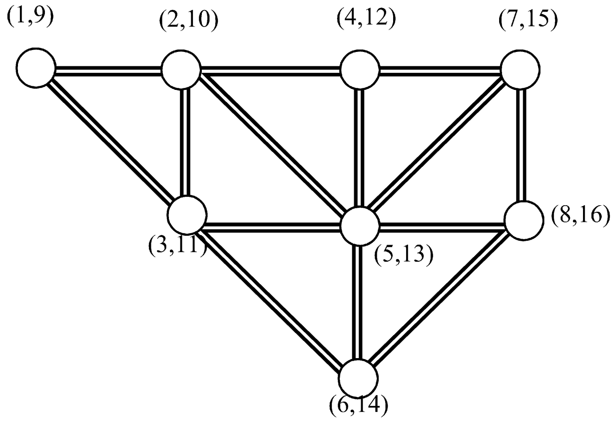

Fig. 6. Two mesh-topology networks with 16 nodes/56 links Node (i, j) is node i in network A and node j in network B.

4.1. Assumptions for other topologies

Similar parameters as Table 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 Section 4.3.

4.2. Comparison table with other topologies

We have derived similar tables (Tables 4 and 5) as Tables 2 and 3 for all the topologies given in Figs. 4–7. But to save space, we hereby only summarize the results in Table 4 for comparison. In Table 4, additional IBC values are considered in the simulation to capture the effect of the reduction in the number of interconnection links as indicated by the values in parentheses. We will discuss various effects and their implications in Section 4.3.

4.3. Further discussion on the results with other topologies

We simulate the merger of two 8-node networks with different topologies as shown in Figs. 1, 4–7. In Table 4, it is evident that under all topologies as IBC increases, the number of interconnection

Table 4
Summary of the merger of two 8-node identical networks with various topologies percentage of fiber cost saving vs interconnection build cost for two 8-node identical networks with five different topologies. The number in ( ) is the number of interconnections used

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 5
Optimal cost vs IBC for two 8-node identical networks with various topologies

Interconnection build cost	Dual-ring	Circle	Tree	Mesh	Bus
1	12,161	11,555	16,820	10,634	15,424
200	–	–	–	–	17,338
400	14,986	14,446	18,860	14,624	17,739
600	16,561	–	–	–	18,139
800	17,706	17,839	20,860	17,145	18,539
900	18,238	18,281	–	–	–
1000	18,875	18,577	21,860	17,940	18,939
1500	–	–	24,360	18,941	–
1800	–	–	25,860	–	–
2000	20,952	20,939	26,580	20,706	20,939
4000	24,503	24,939	30,530	23,950	24,939

links decreases to achieve optimal overall cost. The number of interconnection links eventually reduces to a minimum value of two. Therefore, we can conclude that only two minimum interconnection links are required eventually for all topologies shown.

It is also depicted in Table 4 that as IBC increases, the percentage of cost saving decreases. 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 5 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, we concentrate on the bridge links in a network. We need two fiber links of opposite directions 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, there are more interconnection links. The bus and tree topology will have a higher optimal cost than circle, dual-ring, or mesh topology because less alternative routes are available. This results in more operational fiber links.

When IBC is greater or equal to CIBC, only two interconnection links need to be built. On the location of interconnection links, we will first consider the tree and bus topology. It is found that when

Fig. 7. Two bus-topology networks with 16 nodes/28 links Node (i, j) is node i in network A and node j in network B.

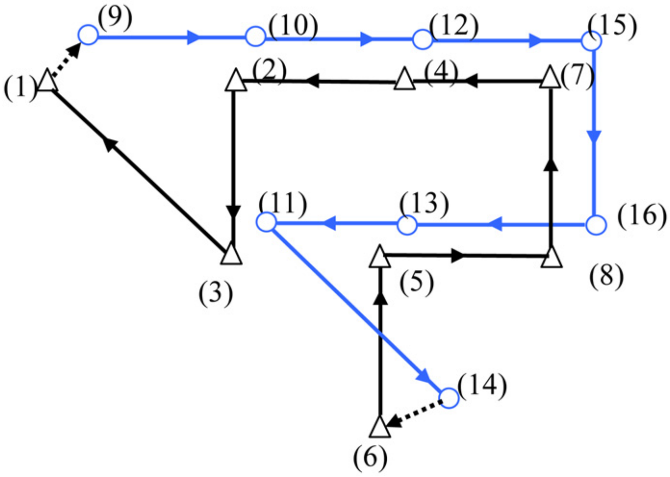

Fig. 8. Two mesh topology networks after merging at CIBC with 16 nodes/16 links (IBC = 1500 of Tables 4 and 5); solid line: operational fiber link; dotted line: interconnection link; (○) and (△) nodes on networks A and B.

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). This is obvious as the two interconnection links and the two bus networks form a unidirectional cycle. The cycle provides complete connection for any two nodes within the two networks. For the tree topology, 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 are to be installed. 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. 5 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 interconnection build cost (IBC).

For the dual-ring, circle and mesh topology illustrated in Figs. 1, 4, and 6, we find that there is a Hamiltonian path that covers all the nodes in one network. With two interconnections installed at the two end nodes of the Hamiltonian path, a unidirectional cycle can be formed that connects all the nodes of the two identical networks. This results in minimum operational fiber links when interconnection links are a minimum of two. For the dual-ring topology, one possible solution is shown in Fig. 2. Whereas for the circle topology, any two adjacent nodes (e.g., node (1, 9) and node (16, 8)) in Fig. 4 can be chosen as the interconnection nodes. This will result in a big cycle that covers all nodes in the two networks. In a simulation, one possible optimized mesh network is shown in Fig. 8. Two Hamiltonian paths are selected and they form a cycle with the two interconnection links installed at the end nodes of the Hamiltonian paths as shown in Fig. 8.

More generally, for other arbitrary topologies, we analyzed the location of the two interconnection links when IBC goes beyond CIBC [19]. We need to find the path that contains the maximum number of directly connected articulation nodes with different groupings. 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 Figs. 5 and 7.

As discussed earlier under the dual-ring topology, analytical Eq. (9) can also apply to other topologies with interconnection links for all co-located nodes. For the tree network illustrated in Fig. 5, all the links are bridges and the minimum number of fiber links required is: $L_{\min} = 2B = 2 \times 7 = 14$. 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 saving in fiber links can be achieved. We note that 48% of cost saving is shown in the simulation results because the interconnection build cost and operating cost are included in the simulation. Likewise, 75% of saving 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 fiber links in one network is preserved and 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. 3. In terms of the number of interconnection links, this is different from case 1 in Table 2 (IBC = 1), which has only eight interconnection links. While for the mesh network in Fig. 6, a maximum of 83.91% cost saving is achieved. The above simulation 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 [17]. Similar cycle forming problems can also be found in the design of survival wavelength division multiplexing (WDM) networks [20].

5. Conclusions

We developed a model and used the CPLEX program to find the optimal cost, the fiber links saved, and the interconnection locations for the optimization in the merger of two networks. We analyzed the effect of interconnection build cost to the number of interconnection links, the location of interconnection links, and the fiber links saved. Our model is also applicable to the optimization in the merger of two non-identical networks.

IBC has direct impact on the number of interconnection nodes and fiber links saved. When IBC is low, more interconnection nodes will be used. Substantial saving can be achieved when IBC is lower than CIBC. No further saving in fiber can be achieved when IBC is higher than CIBC. Network planners may also choose to focus on the two minimum interconnection links case, and determine the location of these interconnection nodes. When the interconnection number is equal to two, which is the minimum number required, we showed that the optimization is reduced to finding a Hamiltonian path that covers all the nodes in one network. If a Hamiltonian path is not available, the optimization is to find a path that contains a maximum number of directly connected articulation nodes with different groupings. Other than these two cases, we need to resort to simulation for finding the optimal interconnection locations for those special topologies. We also provided an analytical formula 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.

Further analysis and studies can be carried out on the interconnection locations with respect to different traffic flow patterns and flow size. Variation of node operating cost will also have strong effect to the interconnection locations. In practice, consideration shall also be given to the interoperability of two networks since this may result in additional cost to network management and interconnection cost. We can also vary the interconnection build cost for different nodes in the model for practical consideration as there may be different interconnection costs in different cities. This will affect the optimal cost and the location of interconnection links. In this study, many parameter values are fixed in order to isolate the effect and to obtain some insights of the characteristics in the optimization of merging two networks.

Acknowledgments

The authors thank Professor J. Leung and Ms. R. Wong of the Chinese University for the support of the CPLEX program. The authors also would like to thank Mr. Y.G. Wen of MIT and Professor G. Yu of the Hong Kong Polytechnic University for their valuable comments. This project is supported in part by Hong Kong Government RGC grant 411006.

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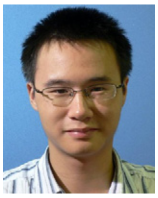

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