PAPER

Optimum Regular Logical Topology for Wavelength Routed WDM Networks

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SUMMARY Several regular topologies have been proposed to be used as the logical topology for WDM networks. These topologies are usually evaluated and compared based on the metrics related to network performance. It can be simply shown that this is generally not sufficient since better network performance can be achieved by increasing more network facilities. However, doing this eventually increases the network cost. Thus, the comparison of topologies must be performed by using an evaluation function that includes both the network performance metric and the network cost. In this paper, we propose a model to find the optimum regular logical topology for wavelength routed WDM networks. ShuffleNet, de Bruijn graph, hypercube, Manhattan Street Network, and GEMNet are the five well-known and commonly used regular topologies compared in this paper. By solving the two subproblems on node placement optimization, and routing and wavelength assignment, we obtain the evaluation function used in the topology comparison. Numerical results show that GEMNet is the optimum logical topology for the wavelength routed WDM networks, where it can take one of the three forms of ShuffleNet, de Bruijn graph, and its own configurations.

key words: *wavelength routed WDM networks, logical topology, node placement optimization, routing and wavelength assignment, optimization*

1. Introduction

Wavelength division multiplexing (WDM) provides a large number of high-speed channels on a single optical fiber by transmitting multiple data streams in the form of independently modulated wavelengths of light in the spectrum passed by a fiber [1].

With tunable transceivers equipped at each network node, lightpaths [2], which are clear optical channels requiring no optoelectronic conversion, can be set up between nodes by assigning an appropriate wavelength to each pair of transmitter and receiver. The connection between a pair of source and destination nodes can be made by using either a single-hop connection if there exists a direct lightpath connecting the two nodes, or a multihop connection via a sequence of lightpaths [3]. In the latter case, optoelectronic conversions are needed at intermediate nodes. The topology of lightpaths is called logical topology (also called virtual topology), which can be adaptively adjusted according to the network status such as traffic changes and failures [4].

The logical topology design problem in WDM networks has been studied extensively in the literature [5]. For example, the design problem has been formulated as an optimization problem to determine the logical topology which yields optimum network performance [6], [7]. In these cases, the logical topologies obtained are of arbitrary type such as the example illustrated in Fig. 1(a).

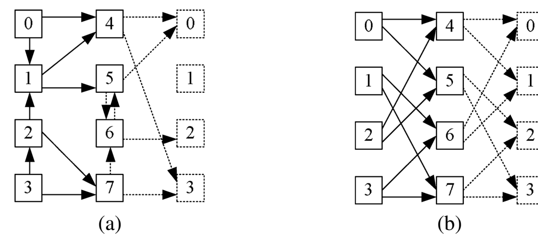

Fig. 1 Logical topologies: (a) arbitrary type, (b) regular type (a ShuffleNet).

On the other hand, there are various studies that proposed to use regular topologies as the logical topology for WDM networks [8]. A well-known example is the ShuffleNet in Fig. 1(b). Compared to arbitrary ones, regular topologies have many good characteristics for being used as the logical topology such as the simplified routing mechanism for reducing processing time required at each node.

Among the several regular topologies, however, there is no clear solution of which topology should be adopted. Most of the studies only suggested that a specific regular topology has good characteristics for WDM networks [3], [8], while other studies just fixed the logical topology to some selected regular topologies without stating any reasons to support their selections [9], [10]. Although there are some studies on the comparison of regular topologies, most of them focused on the evaluation and comparison based on the metrics related to network performance [11], [12]. This is generally not sufficient since better network performance can be achieved by increasing more network facilities and components. However, this eventually increases the network cost. Thus, the comparison of topologies needs an evaluation function that considers the network performance and network cost simultaneously.

An important design problem related to the regular logical topology in WDM networks is the node placement optimization (NPO) problem [13], [14] (also called the node mapping problem [10]). The objective of the NPO is to find an optimum placement of physical network nodes to the nodes in a given logical topology such that a predefined network performance metric is optimized. A good candidate of the performance metric used in the literature is the weighted mean hop distance $\bar{h}$ [14] (defined in Sect. 2).

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However, comparing regular topologies by using $\bar{h}$ only is not appropriate since $\bar{h}$ can be simply decreased by increasing the nodal degree p. In the logical topology, p is the number of transceivers implemented at each node, i.e., each node has p transmitters and p receivers. Clearly, increasing p also increases the cost of the network. Thus, $\bar{h}$ is not a good evaluation function for determining the optimum regular logical topology, and another evaluation function is needed.

We have studied the optimum regular logical topology for WDM networks based on the broadcast-and-select configuration, where the evaluation function consists of two main parts, namely the network performance and network cost [15]. However, the broadcast-and-select based network configuration has several problems when it is used in wide area networks. First, a large-sized network requires an enormous number of wavelengths, typically at least as many as there are nodes in the network. Another problem is the splitting loss. Since the signals transmitted from a node is broadcasted to all other nodes in the network, each node receives only a small fraction of the transmitted power which becomes smaller as the number of nodes increases. To alleviate these problems, another network configuration based on wavelength routing is proposed [10]. The networks employing this configuration are known as wavelength routed networks, which offer several advantages such as wavelength reuse, scalability, and reliability. Therefore, this paper concentrates the study on the wavelength routed WDM networks.

The objective of this paper is to compare a set of well-known and commonly used regular topologies, and determine the optimum topology for wavelength routed WDM networks. ShuffleNet, de Bruijn graph, hypercube, Manhattan Street Network, and GEMNet [8] are the five regular topologies compared in this paper. The evaluation function used in the comparison includes both the network performance metric and the network cost.

The general approach to design a wavelength routed WDM network is to divide the main design problem into two separated subproblems and solve each subproblem independently. For regular logical topologies, the first subproblem is the NPO mentioned above. Solving the NPO yields the logical topology specifying a set of lightpaths connecting between node-pairs. The second subproblem is the routing and wavelength assignment (RWA) [16], [17], where the route of each lightpath on the physical network is determined, and an appropriate wavelength is assigned to each lightpath so as to minimize the total number of wavelengths required in the network. Based on the RWA results, we obtain the details of the physical structure of the network nodes, which reflect the cost of the network. It will be shown later that the evaluation function used in the topology comparison is constructed by the results of the NPO and RWA subproblems.

The rest of this paper is organized as follows. The NPO as well as the regular topologies considered in this paper are discussed in Sect. 2. Section 3 describes the RWA and the node architecture in wavelength routed WDM networks. In Sect. 4, an evaluation function is defined, where the function consists of the metrics related to the network performance and cost. Numerical examples and discussions are given in Sect. 5. Finally, Sect. 6 concludes this paper.

2. Node Placement Optimization

In this section, we discuss the NPO problem in WDM networks, and the regular logical topologies considered in this paper. An illustrative example of the NPO result is also given at the end of this section.

2.1 Problem Statement

Given a set of physical nodes in a WDM network, the matrix specifying the amount of traffic between each node-pair, and a regular topology for use as the logical topology, the objective of the NPO is to find an optimum placement of the physical nodes into the regular topology such that a predefined optimality criterion is satisfied. In other words, we need the optimum mapping between the physical nodes and the nodes in the regular topology.

Let n be the number of physical nodes, N be the number of nodes in the regular topology, $\mathbf{H} = [h_{ij}]$ be the distance matrix where h_{ij} is the hop distance from node i to j in the regular topology, and $\mathbf{F} = [f_{kl}]$ be the traffic matrix where f_{kl} denotes the traffic rate from node k to l. Due to the modular property of several regular topologies, it is possible that $n < N$. In these cases, we need to introduce $N - n$ auxiliary nodes to the physical network, where $f_{kl} = 0$ when k or l is an auxiliary node. Note that the auxiliary nodes are added for analysis purposes only. Since they are not practically implemented, the logical topologies obtained are injured regular topologies [10].

For a given node placement pattern $\Pi = \{\pi(i)\}$ whose element $\pi(i)$ is the physical node placed at node i in the regular topology, we can define the weighted mean hop distance $\bar{h}$ [14] as

$$\bar{h} = \frac{1}{F} \sum_{i=1}^{N} \sum_{j=1}^{N} h_{ij}\, f_{\pi(i)\pi(j)}, \tag{1}$$

where $F = \sum_{k=1}^{N} \sum_{l=1}^{N} f_{kl}$.

Thus, the optimum solution of the NPO problem is the placement Π which minimizes $\bar{h}$.

Obviously, the NPO problem is equivalent to a well-known combinatorial optimization problem called the quadratic assignment problem (QAP) [18]. Since the QAP is NP-complete, we have that the NPO problem is also NP-complete. Although some heuristic algorithms have been proposed for solving the NPO problem [13], [14], they have some drawbacks on the diversity of the solutions obtained. As a consequence, this paper adapts the metaheuristics previously proposed for the QAP to solve the NPO problem. They are evolutionary algorithms [19] and tabu search [20]. The performance of these methods is discussed in Appendix A.

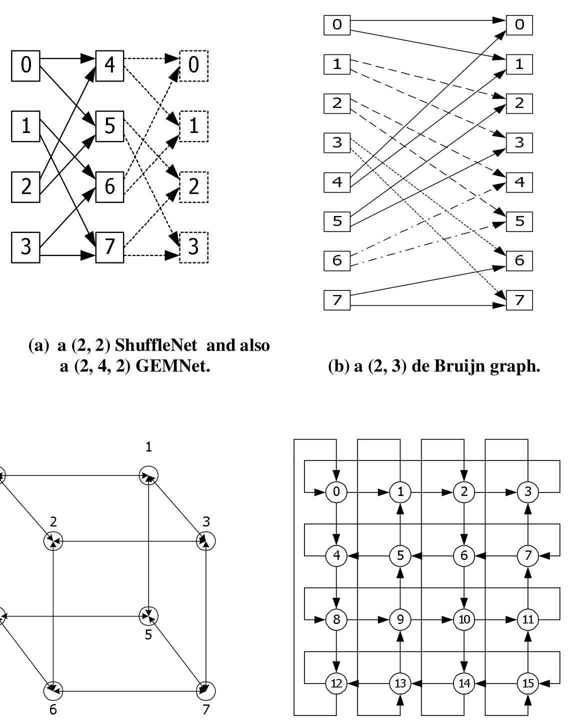
2.2 Regular Logical Topologies

As mentioned above, this paper considers the following five well-known regular topologies. For all topologies, there is a common parameter p, which is the nodal degree. Recall that N is the number of nodes.

- ShuffleNet [21]: a (p, k) ShuffleNet has $N = kp^k$, where k is the number of columns.
- de Bruijn graph [22]: a (p, D) de Bruijn graph has $N = p^D$, where D is the diameter of the topology.
- hypercube [23]: a hypercube has $N = 2^p$.
- Manhattan Street Network (MSN) [24]: an MSN has $p = 2$, and $N = R \times C$, where R and C are the number of rows and columns, respectively.
- GEMNet [25]: a (K, M, p) GEMNet has $N = K \times M$, which are arranged in K columns and M rows, where $K \geq 1$ and $M \geq p$.

Some examples of the regular topologies are depicted in Fig. 2. Note that a GEMNet can reduce to a ShuffleNet when $M = p^K$, and also to a de Bruijn graph of diameter D when $M = p^D$ and $K = 1$.

Physically, a link connecting a node-pair in the logical topology represents a lightpath between the two nodes, while the nodal degree p is the number of transceivers equipped at each node. For the regular topologies in Figs. 2(a)–(d), the values of p are 2, 2, 3, and 2, respectively.



(a) a (2, 2) ShuffleNet and also a (2, 4, 2) GEMNet. **(b) a (2, 3) de Bruijn graph.**

(c) a hypercube network. **(d) Manhattan Street Network (MSN).**

Fig. 2 Regular topologies: (a) a (2, 2) ShuffleNet and also a (2, 4, 2) GEMNet, (b) a (2, 3) de Bruijn graph, (c) an 8-node hypercube, and (d) a 16-node MSN.

Since increasing p provides more paths between node-pairs, $\bar{h}$ is decreased. Thus, a regular topology with large p generally has small $\bar{h}$ [11], [12]. However, $\bar{h}$ is obviously not a good evaluation function for determining the optimum regular topology since a large value of p results in the high network cost. Clearly, using other network performance metrics as the evaluation function in the topology comparison is also not appropriate since better network performance can be achieved by increasing more network facilities, e.g., increasing p. However, this eventually increases the network cost. Thus, another evaluation function is needed in the comparison where the performance metric and network cost are both considered in the function [15]. In this paper, an evaluation function is defined in the way that one of its components is $\bar{h}$ which is used to measure the network performance.

2.3 An Illustrative Example

This section gives an example of solving the NPO problem. The physical WDM network is the 8-node network in Fig. 3. Note that each physical link represents a pair of input/output optical fibers to a node. For the logical topology, we investigate the embedding of the 8-node ShuffleNet with $p = 2$ in Fig. 2(a). The traffic matrix is

$$\mathbf{F} = \begin{bmatrix} 0.00 & 0.36 & 0.55 & 0.62 & 0.08 & 0.50 & 0.79 & 0.99 \\ 0.99 & 0.00 & 0.46 & 0.64 & 0.93 & 0.36 & 0.77 & 0.73 \\ 0.07 & 0.10 & 0.00 & 0.57 & 0.73 & 0.72 & 0.81 & 0.82 \\ 0.76 & 0.80 & 0.57 & 0.00 & 0.66 & 0.30 & 0.70 & 0.08 \\ 0.53 & 0.26 & 0.61 & 0.89 & 0.00 & 0.81 & 0.23 & 0.97 \\ 0.31 & 0.02 & 0.95 & 0.30 & 0.48 & 0.00 & 0.59 & 0.23 \\ 0.84 & 0.36 & 0.96 & 0.91 & 0.45 & 0.53 & 0.00 & 0.64 \\ 0.17 & 0.34 & 0.46 & 0.93 & 0.14 & 0.03 & 0.59 & 0.00 \end{bmatrix}.$$

After solving the NPO problem, we obtain the optimum solution as illustrated in Fig. 4 with $\bar{h} = 1.83$.

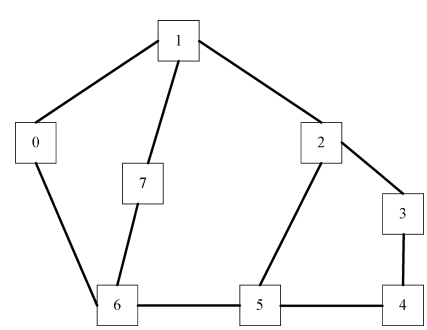


Fig. 3 An 8-node WDM network.

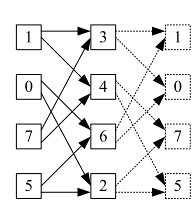


Fig. 4 The optimum node placement in the ShuffleNet ($p = 2$).

Each link in the logical topology represents a lightpath between a node-pair. From the above result, we can see that some lightpaths must be embedded in the physical network by using multiple fibers via intermediate nodes.

3. Routing and Wavelength Assignment

This section discusses the RWA problem and the node architecture in wavelength routed WDM networks.

3.1 Problem Statement

The result of the NPO problem is a set of lightpaths connecting between node-pairs. Then the second subproblem of the WDM network design is the RWA, which finds a route and assigns a wavelength to each lightpath such that the overall number of wavelengths required in the network, Λ, is minimum [17].

For the lightpath routing, this paper considers the shortest-path routing [10], [16] due to its simplicity and effectiveness. Thus, each lightpath is accommodated to the physical network via the shortest path between the source and destination nodes.

After the routing of all lightpaths is completed, wavelength assignment to each lightpath is conducted with the constraint that different wavelengths must be assigned to the lightpaths passing through the same physical link. We also assume that there are no wavelength converters in the network, and a lightpath must be assigned with a single wavelength along the path, i.e., the wavelength continuity constraint.

It is important to note that the wavelength assignment problem is equivalent to a well-known NP complete problem called the graph coloring problem [17], where the minimum Λ is equal to the minimum number of colors (the chromatic number) of the equivalent graph. Several efficient heuristics and metaheuristics have been proposed to solve the graph coloring problem [26]. Thus, this paper applies these methods to solve the wavelength assignment problem in WDM networks. See Appendix A for the performance of these methods.

3.2 An Illustrative Example

From the example in the last section, we can solve the RWA problem for the set of lightpaths obtained from the NPO result. The optimum solution obtained has $\Lambda = 4$. One part of the result is illustrated in Fig. 5, where the wavelength assignment of all lightpaths corresponding to node 1 is shown. The four wavelengths used are λ_1, λ_2, λ_3, and λ_4.

Clearly, there are three types of lightpaths related to each network node. The first type is the lightpaths that pass through or cross connect the node, while the second and third type are those having the node as the source and destination node, respectively. For node 1 in Fig. 5, we have that the lightpaths 0-2, 2-7, 3-0, and 7-3 are of the first type, the lightpaths 1-3 and 1-4 are of the second type, and the lightpaths 3-1 and 6-1 are of the third type.

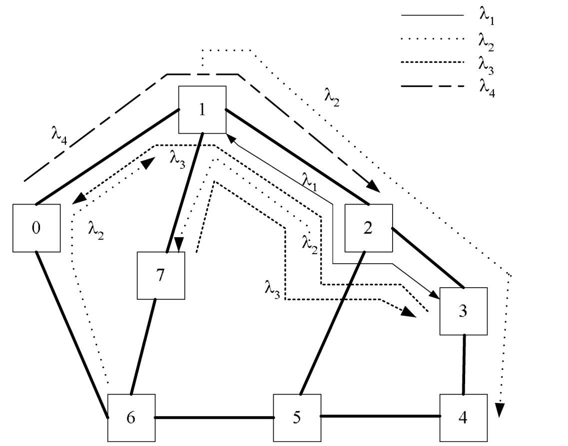


Fig. 5 The wavelength assignment of the lightpaths corresponding to node 1.

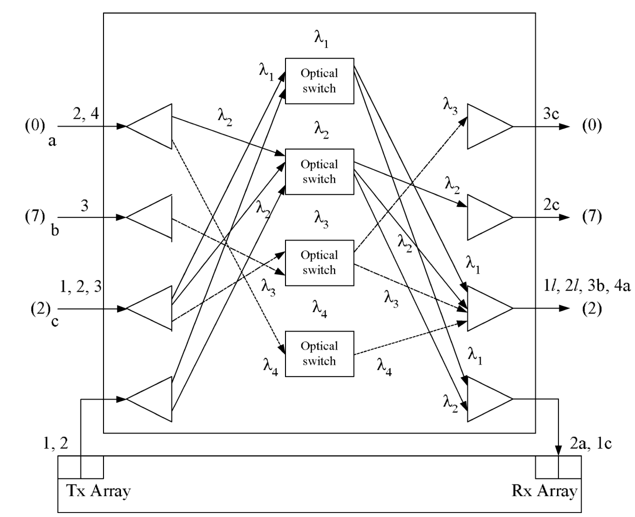


Fig. 6 The optical routing architecture at node 1.

3.3 Node Architecture

In a wavelength routed WDM network, each node has capability to perform wavelength routing. Figure 6 shows the structural architecture of node 1 in the above example [6], [10], [16].

The lightpaths from an input optical fiber or the transmitter array are separated according to their wavelength by a grating demultiplexer. The signals of each wavelength are then forwarded to the optical switch for that wavelength. Thus, the number of optical switches equipped at each node is equal to Λ, i.e., one per wavelength.

Each optical switch routes the lightpaths to their desired output. For the lightpaths of the first type, which cross connect the node, they are routed to the desired output fiber. For example, the lightpath 0-2 using the wavelength λ_4 from the input fiber a (node 0) is routed through the switch λ_4 to the output fiber of node 2 (denoted by 4a in Fig. 6).

For the lightpaths of the second type, which have the node as the source node, they are also routed to the desired output fiber. In this case, the signals of these lightpaths are sent from the transmitter array. One example is the lightpath 1-4 using λ_2, which is routed to the output fiber of node 2 (denoted by $2l$ in Fig. 6).

The lightpaths of the third type, which have the node as the destination node, are routed to the receiver array for lightpath termination. One example is the lightpath 6-1 using λ_2 from the input fiber a (node 0), which is routed through the switch λ_2 to the receiver (denoted by 2a in Fig. 6).

The lightpaths to an output fiber or the receiver array are grouped together by a grating multiplexer.

For each network node, the number of transceivers is equal to the nodal degree p. Recall that $p = 2$ in Fig. 6. In this example, the transceivers at node 1 are tuned to the wavelengths λ_1 and λ_2.

4. Logical Topology Optimization

This section defines an evaluation function used in the topology comparison for determining the optimum regular logical topology for WDM networks.

4.1 Evaluation Function

As mentioned above, it is not appropriate to use a network performance metric as the evaluation function for the topology comparison. Thus we need another function that considers both the network performance and cost simultaneously. To define such kind of evaluation function, this paper follows the function developed in Ref. [15].

Generally, the evaluation function is in the form of network performance per unit cost, which is needed to be maximized for finding an optimum regular topology. This paper adopts the network throughput for the part of performance metric in the evaluation function. The throughput T can be approximated [7] by

$$T \leq C/\bar{h}, \tag{2}$$

where C is the network capacity, and $\bar{h}$ is the weighted mean hop distance defined in the NPO. Clearly, maximizing T is equivalent to minimizing $\bar{h}$ [7].

We let D be the network cost, and define the evaluation function as T/D, i.e., performance per cost. Hence, maximizing T/D is equivalent to minimizing $\bar{h} \times D$. As a consequence, the evaluation function X used in the topology comparison is then defined as

$$X = \bar{h} \times D, \tag{3}$$

which is needed to be minimized.

4.2 Network Cost Model

For simplicity, we assume that the network cost D consists of the node costs only, where link costs are neglected. Thus, we have

$$D = \sum_{i=1}^{n} D_i, \tag{4}$$

where D_i is the cost of node i, and n is the number of nodes in the physical network.

The cost model developed in Ref. [27] is used in the calculation of D_i. In the node, the most expensive elements are the optical switches and the transceivers. The cost of an optical switch can be measured by the number of 2×2 crosspoint elements contained in the switch. In this model, it is assumed that the switches are implemented using banyan switches, each of which requires $\frac{M}{2}\log_2 M$ crosspoint elements, where M is the number of input/output ports on a switch, which is also the number of ports of a node. In addition, the number of optical switches equipped in a node is equal to the number of wavelengths Λ. We assume that the cost of a 2×2 crosspoint element is one unit, while that of a transceiver is α units. Therefore, the node cost D_i can then be given by

$$D_i = \Lambda.\left(\frac{M_i}{2}\log_2 M_i\right) + \alpha.p, \tag{5}$$

where M_i is the number of input/output ports of node i, and p is the nodal degree.

It is obvious that the evaluation function defined in this paper consists of two main parts, each of which is the result of the NPO and RWA subproblems.

5. Numerical Results and Discussions

This section provides numerical results and discussions on the optimum regular logical topology for wavelength routed WDM networks based on the evaluation function X defined above.

We consider WDM networks with the number of physical nodes n varied from 5 to 32. The physical network topology is randomly generated, where the physical nodal degree is between 2 to 4. An example of the physical topology is given in Fig. 7 for the case of $n = 5$.

When a regular topology is applied to the physical network, we choose the pattern of the regular topology with minimum N such that $N \geq n$. For example, a ShuffleNet

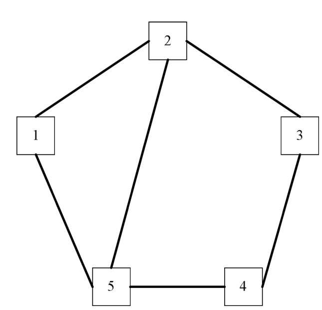


Fig. 7 The physical network topology for the case $n = 5$.

Table 1 The average value of $\bar{h}$ for different logical topologies and network sizes. For each case, the nodal degree p is given in the parenthesis.

n	Average of $\bar{h}$														
	$\gamma = 1$					$\gamma = 10$					$\gamma = 100$				
	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem
5	1.65 (2)	1.65 (2)	1.61 (2)	1.41 (3)	1.51 (2)	1.46 (2)	1.46 (2)	1.40 (2)	1.23 (3)	1.35 (2)	1.40 (2)	1.40 (2)	1.30 (2)	1.15 (3)	1.32 (2)
8	1.81 (2)	1.81 (2)	1.89 (2)	1.56 (3)	1.81 (2)	1.73 (2)	1.73 (2)	1.75 (2)	1.50 (3)	1.73 (2)	1.68 (2)	1.68 (2)	1.65 (2)	1.17 (3)	1.65 (2)
13	1.97 (3)	2.59 (2)	2.49 (2)	1.90 (4)	2.41 (2)	1.73 (3)	2.20 (2)	2.11 (2)	1.55 (4)	2.05 (2)	1.50 (3)	1.81 (2)	1.75 (2)	1.23 (4)	1.71 (2)
16	2.02 (3)	2.68 (2)	2.65 (2)	1.96 (4)	2.02 (3)	1.83 (3)	2.35 (2)	2.31 (2)	1.66 (4)	1.83 (3)	1.57 (3)	1.98 (2)	1.89 (2)	1.35 (4)	1.57 (3)
18	2.05 (3)	3.27 (2)	1.70 (5)	2.15 (5)	1.70 (5)	1.87 (3)	2.67 (2)	1.53 (5)	1.80 (5)	1.53 (5)	1.61 (3)	2.10 (2)	1.31 (5)	1.35 (5)	1.31 (5)
25	2.13 (4)	4.23 (2)	1.74 (5)	2.36 (5)	1.74 (5)	1.97 (4)	3.57 (2)	1.62 (5)	2.05 (5)	1.62 (5)	1.72 (4)	2.56 (2)	1.45 (5)	1.55 (5)	1.45 (5)
32	2.17 (4)	4.75 (2)	3.49 (2)	2.44 (5)	2.17 (4)	2.03 (4)	4.03 (2)	3.17 (2)	2.15 (5)	2.03 (4)	1.74 (4)	2.62 (2)	2.56 (2)	1.58 (5)	1.74 (4)

Table 2 The average value of X for $\gamma = 1$.

n	Average value of X														
	α=1					α=10					α=100				
	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem
5	131.9	121.8	109.6	151.0	78.7	280.2	270.1	264.2	341.4	214.9	1763.4	1753.3	1800.5	2244.9	1576.6
8	213.8	213.8	199.1	241.6	199.1	473.7	473.7	472.5	578.3	472.5	3069.3	3069.3	3196.2	3945.8	3069.3
13	819.3	796.6	737.5	920.3	583.9	1509.0	1401.5	1320.4	1809.9	1148.3	8406.2	7450.4	7149.3	10706.6	6792.4
16	1100.4	1114.7	1059.7	1316.2	1059.7	1974.3	1886.2	1823.0	2444.6	1823.0	10713.7	9601.8	9455.8	13728.4	9455.8
18	1493.4	1987.6	2095.1	2626.8	1493.4	2487.9	3046.7	3470.2	4365.9	2487.9	12432.5	13638.2	17221.5	21756.9	12432.5
25	3973.8	3968.7	3486.7	4736.7	3486.7	5946.5	5894.5	5443.4	7395.1	5443.4	25673.8	25152.4	25009.9	33978.8	25009.9
32	5187.0	6912.4	4307.6	6630.9	4307.6	7683.4	9665.1	6316.1	10148.8	6316.1	32647.2	37192.1	26401.2	45328.0	26401.2

Table 3 The average value of X for $\gamma = 10$.

n	Average value of X														
	α=1					α=10					α=100				
	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem
5	123.0	122.8	114.2	142.2	69.4	257.7	257.5	239.5	306.2	188.5	1604.6	1604.3	1492.3	1946.5	1399.0
8	193.2	193.2	178.5	237.3	178.5	442.7	442.7	433.8	561.5	433.8	2936.7	2936.7	2942.6	3803.7	2936.7
13	752.9	651.7	587.0	787.4	508.3	1360.1	1166.0	1080.3	1512.8	987.6	7432.4	6309.3	6013.0	8766.8	5779.9
16	1275.2	921.8	886.3	1154.1	886.3	2067.9	1599.2	1550.7	2108.6	1550.7	9995.1	8373.0	8194.9	11652.9	8194.9
18	1283.3	1330.9	2137.9	2134.1	1283.3	2189.9	2204.6	3374.8	3596.1	2189.9	11256.8	10941.6	15743.6	18215.9	11256.8
25	3703.0	3242.0	2958.2	4371.8	2958.2	5526.5	4867.6	4779.9	6672.4	4779.9	23761.9	21123.8	22996.8	29678.7	22996.8
32	5007.8	4199.7	3550.7	5452.5	3550.7	7342.9	6518.1	5377.2	8542.7	5377.2	30694.0	29702.1	23642.1	39445.1	23642.1

with $N = 8$ is chosen for the network with $n = 5$. In the case of GEMNet which can have multiple configurations for a given value of N, we let it take the form of ShuffleNet or de Bruijn graph if possible, otherwise we follow the guidelines in Ref. [25] for the setting of good configurations.

Two types of traffic models are studied. The first type is the uniformly distributed random traffic, where the traffic rate between each node-pair in the network is randomly set between 0 and 1. The second type is the non-uniformly distributed random traffic. In this traffic model, about 10% of nodes are specified as server nodes each of which has its own group of client nodes to serve. The traffic rate from a server node to a client node it serves is a uniformly distributed random number between 0 and γ, while the traffic rate for the rest of node-pairs is randomly set between 0 and 1. We call γ the traffic skew factor. The case of $\gamma = 1$ is equivalent to the uniformly distributed random traffic model. This paper sets γ equal to 1, 10, and 100.

For each network size and traffic model, ten traffic patterns are generated and each regular topology is applied to be the logical topology.

Then the NPO problem is solved for each problem instance. Table 1 gives the average value of $\bar{h}$ for each regular topology whose p is given in the parentheses. In the table, sh is ShuffleNet, msn is Manhattan Street Network, deB is de Bruijn graph, hyp is hypercube, and gem is GEMNet. Due to the space limitation, only some values of n are presented. Table 1 shows that $\bar{h}$ is generally decreased when p is increased as expected.

Next, the RWA problem is solved to determine Λ. Then we can calculate the network cost D in which the cost ratio α is varied for three cases: 1, 10, and 100. Finally, X can be obtained for each problem instance. Tables 2, 3, and 4 summarize the results on the optimum logical topology denoted by the shaded area at which the average value of X is minimum. See also Appendix B for the worst case analysis of X.

The results clearly show that GEMNet is optimum for almost of the cases, especially, it is the only one optimum topology for $n = 5$ and 13. Note that GEMNet can realize networks of all n, i.e., we can always construct an n-node GEMNet. Obviously, other topologies need auxiliary nodes for $n = 5$ and 13.

Since GEMNet can reduce to ShuffleNet and de Bruijn graph, the two topologies are also optimum in some cases of n. Note that ShuffleNet can realize the cases of $n = 8, 18,$

Table 4 The average value of X for $\gamma = 100$.

n	Average value of X														
	α=1					α=10					α=100				
	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem
5	100.1	94.6	98.8	108.9	68.8	225.8	235.6	215.5	263.8	188.0	1483.0	1568.9	1382.1	1812.8	1379.4
8	183.5	183.5	189.7	246.6	183.5	425.0	425.0	427.0	563.5	425.0	2839.9	2839.9	2800.2	3732.2	2800.2
13	650.5	579.8	517.7	615.9	454.7	1174.2	1002.9	927.4	1189.7	854.1	6411.1	5233.6	5024.7	6927.4	4848.5
16	877.9	836.3	741.4	885.2	741.4	1556.2	1405.1	1285.7	1662.8	1285.7	8338.6	7093.1	6728.9	9438.8	6728.9
18	1194.2	1133.5	1794.7	1819.7	1194.2	1978.1	1819.4	2856.4	2913.4	1978.1	9817.3	8678.5	13472.9	13850.4	9817.3
25	2980.8	2282.3	2663.9	3092.2	2663.9	4573.4	3444.7	4290.4	4839.3	4290.4	21498.9	15068.5	20555.3	22310.8	20555.3
32	3897.3	2985.4	2959.6	3866.7	2959.6	5901.5	4492.7	4431.2	6143.6	4431.2	25943.3	19566.3	19146.4	28911.5	19146.4

Table 5 The average value of X for GEMNet and MSN.

n	Average value of X					
	α = 1		α = 10		α = 100	
	msn	gem	msn	gem	msn	gem
18 (γ =10)	1330.9	1102.5	2204.6	1891.8	10941.6	9785.5
25 (γ =10)	3242.0	2519.3	4867.6	3809.7	21123.8	16713.3
18 (γ =100)	1133.5	1124.9	1819.4	1780.4	8678.5	8335.6
25 (γ =100)	2282.3	2017.6	3444.7	3067.9	15068.5	13571.0

and 32, while de Bruijn graph can realize $n = 8, 16, 25$, and 32. For the cases of n which can be realized by only one topology either ShuffleNet or de Bruijn graph, that topology is the optimum logical topology. For the cases of n which can be realized by both topologies, one of them is the optimum. In the case of $n = 8$, the optimum topology depends on α and γ. However, the values of X of the two topologies are not so different since their p's are the same. For the case of $n = 32$, de Bruijn graph is the optimum topology. This is because it has smaller p than ShuffleNet.

MSN is optimum in some cases. For example, it is optimum when $n = 8$ at which ShuffleNet is optimum, since the two topologies are equivalent at this n. Moreover, MSN is better than GEMNet at $n = 18$ and 25 when $\gamma = 10$ and $\alpha = 100$, and $\gamma = 100$. In these cases, MSN has larger $\bar{h}$ since it always fixes p to 2. However, this property of small p leads to smaller D and eventually yields smaller X. Although GEMNet has smaller $\bar{h}$, the decreasing in $\bar{h}$ is less than the increasing in D compared to MSN. When $n = 32$, MSN is worse than GEMNet, which is in the form of de Bruijn graph, because they have the same p. Since small p is one of the good property of the optimum topology, we further investigate the GEMNet with small p for $n = 18$ and 25 by setting $p = 2$ and using (2, 9, 2) and (1, 25, 2) GEMNets, respectively. The results are given in Table 5 where GEMNet is better than MSN in all cases.

In the numerical results, note that hypercube is never optimum. Although it has large p which gives small $\bar{h}$, its D is large and this results in large X.

The cost ratio α and the traffic skew factor γ have almost no effect on the optimum topology. Although some effects are observed in the case of $n = 8$, where the optimum is either ShuffleNet or de Bruijn graph, the two topologies have almost the same X as mentioned above. Thus, the above results are widely applicable, where the optimum topology strongly depends only on the size of the network.

6. Conclusions

This paper evaluates and compares a set of well-known regular topologies for use as the logical topology of wavelength routed WDM networks. Unlike the previous studies which usually use network performance metrics in the topology comparison, this paper defines an evaluation function that simultaneously considers the network performance metric and network cost. Numerical results show that GEMNet is the optimum logical topology, where it can take one of the three forms: ShuffleNet, de Bruijn graph, or its own configurations. The results of this paper can be used for the selection of the logical topology for WDM networks.

References

[1] P.E. Green, Fiber Optic Networks, Prentice-Hall, Englewood Cliffs, NJ, 1993.

[2] I. Chlamtac, A. Faragó, and T. Zhang, "Lightpath (wavelength) routing in large WDM networks," IEEE J. Sel. Areas Commun., vol.14, no.5, pp.909–913, June 1996.

[3] B. Mukherjee, "WDM-based local lightwave networks part II: Multihop systems," IEEE Netw., vol.6, no.4, pp.20–32, July 1992.

[4] J.-F.P. Labourdette and A.S. Acampora, "Logically rearrangeable multihop lightwave networks," IEEE Trans. Commun., vol.39, no.8, pp.1223–1230, Aug. 1991.

[5] R. Dutta and G.N. Rouskas, "A survey of virtual topology design algorithms for wavelength routed optical networks," Optical Netw. Mag., vol.1, no.1, pp.73–89, Jan. 2000.

[6] R. Ramaswami and K.N. Sivarajan, "Design of logical topologies for wavelength-routed optical networks," IEEE J. Sel. Areas Commun., vol.14, no.5, pp.840–851, June 1996.

[7] D. Banerjee and B. Mukherjee, "Wavelength-routed optical networks: Linear formulation, resource budgeting tradeoffs, and a reconfiguration study," IEEE/ACM Trans. Netw., vol.8, no.5, pp.598–607, Oct. 2000.

[8] S. Banerjee, V. Jain, and S. Shah, "Regular multihop logical topologies for lightwave networks," IEEE Commun. Surveys, vol.2, no.1, pp.2–18, First Quarter 1999.

[9] I. Chlamtac, A. Ganz, and G. Karmi, "Lightnets: Topologies for high-speed optical networks," J. Lightwave Technol., vol.11, no.5/6, pp.951–961, May/June 1993.

[10] B. Mukherjee, S. Ramamurthy, D. Banerjee, and A. Mukherjee, "Some principles for designing a wide-area optical network," Proc. IEEE INFOCOM'94, pp.110–119, Toronto, Canada, June 1994.

[11] C. Rose, "Mean internodal distance in regular and random multihop networks," IEEE Trans. Commun., vol.40, no.8, pp.1310–1318, Aug. 1992.

[12] M.A. Marsan, A. Bianco, E. Leonardi, and F. Neri, "Topologies for wavelength-routing all-optical networks," IEEE/ACM Trans. Netw., vol.1, no.5, pp.534–546, Oct. 1993.

[13] K.L. Yeung and T.-S.P. Yum, "Node placement optimization in ShuffleNets," IEEE/ACM Trans. Netw., vol.6, no.3, pp.319–324, June 1998.
[14] H.L.T. Wong and K.L. Yeung, "Lookahead algorithm for node placement optimization in ShuffleNets," IEICE Trans. Commun., vol.E83-B, no.7, pp.1527–1533, July 2000.
[15] J. Nittayawan and S. Runggeratigul, "Optimum logical topology for WDM networks," Proc. ITC-CSCC 2002, pp.1371–1374, Phuket, Thailand, July 2002.
[16] R. Ramaswami and K.N. Sivarajan, "Routing and wavelength assignment in all-optical networks," IEEE/ACM Trans. Netw., vol.3, no.5, pp.489–500, Oct. 1995.
[17] D. Banerjee and B. Mukherjee, "A practical approach for routing and wavelength assignment in large wavelength-routed optical networks," IEEE J. Sel. Areas Commun., vol.14, no.5, pp.903–908, June 1996.
[18] R.E. Burkard, "Quadratic assignment problems," Eur. J. Oper. Res., vol.15, pp.283–289, 1984.
[19] P. Merz and B. Freisleben, "Fitness landscape analysis and memetic algorithms for the quadratic assignment problem," IEEE Trans. Evol. Comput., vol.4, no.4, pp.337–352, Nov. 2000.
[20] J. Skorin-Kapov, "Extensions of a tabu search adaptation to the quadratic assignment problem," Computers and Operations Research, vol.21, no.8, pp.855–865, 1994.
[21] M.G. Hluchyj and M.J. Karol, "ShuffleNet: An application of generalized perfect shuffles to multihop lightwave networks," J. Lightwave Technol., vol.9, no.10, pp.1386–1397, Oct. 1991.
[22] K.N. Sivarajan and R. Ramaswami, "Lightwave networks based on de Bruijn graphs," IEEE/ACM Trans. Netw., vol.2, no.1, pp.70–79, Feb. 1994.
[23] P.W. Dowd, "Wavelength division multiple access channel hypercube processor interconnection," IEEE Trans. Comput., vol.41, no.10, pp.1223–1241, Oct. 1992.
[24] S.W. Park and Y.C. Kim, "A virtual topology for WDM multihop lightwave networks," Proc. INFOCOM'95, pp.701–708, Boston, MA, 1995.
[25] J. Iness, S. Banerjee, and B. Mukherjee, "GEMNET: A generalized, shuffle-exchange-based, regular, scalable, modular, multihop, WDM lightwave network," IEEE/ACM Trans. Netw., vol.3, no.4, pp.470–476, Aug. 1995.
[26] P. Galinier and J.-K. Hao, "Hybrid evolutionary algorithms for graph coloring," J. Combinatorial Optimization, vol.3, pp.379–397, 1999.
[27] J.P. Jue, D. Datta, and B. Mukherjee, "A new node architecture for scalable WDM optical networks," Proc. ICC'99, vol.3, pp.1714–1718, Vancouver, Canada, June 1999.

Appendix A: Performance Evaluation of the Heuristics for WDM Network Design Subproblems

First, we evaluate the performance of the heuristics used for solving the NPO problem. As an example, the solutions and computation time of the evolutionary algorithms (EAs) are compared with global optima obtained from the technique based on complete enumeration (CE). The comparison results are presented in Table A· 1 for the case of GEMNet with $\gamma = 1$.

For each case, the average value of global optima, $\bar{h}$, of the ten problem instances is listed in the parenthesis next to the average of the EA solutions. Although there is no guarantee that heuristics such as EAs always give global optima, the EAs used in this paper can find the global optima of all problem instances when $n = 5$ and 8. When $n = 13$, the EA

Table A· 1 The performance evaluation of the methods for the NPO problem.

n	EA solution	EA time (s)	CE time (s)
5	1.51 (1.51)	1.48	0.00024
8	1.81 (1.81)	5.06	0.07184
13	2.41 (2.38)	19.17	26110.8
16	2.02 (–)	35.80	–
18	1.70 (–)	50.01	–
25	1.74 (–)	130.88	–
32	2.17 (–)	268.54	–

Table A· 2 The performance evaluation of the methods for the RWA problem. n_l is the number of lightpaths in each case.

n, p, n_l	solution	time (s)	CE time (s)
5, 2, 10	2.1 (2.1)	0.00001	2.38
8, 2, 16	2.8 (2.8)	0.00002	17935.85
13, 2, 26	3.6 (–)	0.00005	–
16, 2, 32	4.6 (–)	0.00007	–
18, 3, 54	6.5 (–)	0.00020	–
25, 5, 125	12.7 (–)	0.00129	–
32, 2, 64	6.1 (–)	0.00026	–

solutions are worse than the global optima for only 1.26% in average. According to the nature of the NPO problem, the computation time needed to find global optima increases rapidly with n. For $n = 13$, CE needs about 7 hours to find a global optimum, while EAs consume only 19.17 seconds. Note that all experiments are conducted under the Linux environment on a personal computer with CPU Celeron 2.4 GHz. For larger n, CE could not give global optima in acceptable time (e.g., the estimated time for $n = 16$ is longer than one year). Thus, it can be concluded that the heuristics used for solving the NPO problem have good performance in finding optimum solutions.

Next, we examine the heuristics for the RWA problem. Largest-first and smallest-last are the two heuristics compared to CE as presented in Table A· 2.

Note that the number of lightpaths n_l can be computed by $n_l = n \times p$. Each solution in the table is the average number of wavelengths for the ten problem instances of each n. Clearly, the heuristics can give the global optima for small n with much shorter time. For $n = 8$, CE needs nearly 5 hours to find a global optimum. Thus, the heuristics used in this paper for the RWA problem also have very good performance in finding optimum solutions with short computation time.

Appendix B: Worst Case Analysis of Logical Topology Comparison

Table A· 3 summarizes the worst case analysis of logical topology comparison. The results are similar to those obtained in the analysis based on the average value of X. It can be seen clearly that GEMNet outperforms other topologies in the worst case analysis. Due to the space limitation, the results of the case $\gamma = 1$ are only given. However, other cases are also similar to the analysis based on the average value of X.

Table A· 3 The worst case results of X for $\gamma = 1$.

n	The worst value of X														
	α=1					α=10					α=100				
	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem	sh	msn	deB	hyp	gem
5	153.9	153.9	149.4	162.1	106.4	307.8	307.8	298.8	388.8	243.2	1846.8	1846.8	1792.8	2336.0	1632.8
8	263.5	263.5	318.6	287.0	263.5	527.0	527.0	579.2	581.4	527.0	3127.7	3127.7	3273.3	3994.2	3127.7
13	1027.6	999.7	957.3	1130.7	649.0	1722.6	1605.8	1537.6	2024.6	1220.0	8672.4	7666.4	7340.8	10963.4	6929.6
16	1396.6	1377.3	1351.7	1528.8	1351.7	2273.6	2152.0	1915.2	2652.0	1915.2	11043.2	9899.2	9715.2	14009.6	9715.2
18	1810.5	2498.5	2274.1	2889.8	1810.5	2803.7	3558.1	3650.7	4639.3	2803.7	12735.1	14153.9	17417.5	22133.6	12735.1
25	4918.4	5195.1	4338.1	5581.1	4338.1	6826.4	7089.6	6292.8	8258.6	6292.8	30559.2	27314.5	25859.9	35033.6	25859.9
32	6527.4	9523.2	4914.0	8388.8	4914.0	9027.2	12288.0	6924.2	11916.8	6924.2	34025.6	39936.0	27026.6	47196.8	27026.6

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