Optimum Logical Topology for WDM Networks

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Abstract: This paper compares four network configurations for using as the logical topology in multihop wavelength division multiplexing (WDM) networks. The regular network configurations studied in this paper are ShuffleNet, de Bruijn graph, hypercube, and Manhattan street network. Instead of using the weight mean hop distance $\bar{h}$ of node placement problem for comparing optimum logical topology, we introduce a new objective function that includes $\bar{h}$ and the network cost. It can be seen that the network cost strongly depends on the logical topology selected for the implementation of the network. The objective of this paper is to find an optimum logical topology for WDM networks that gives low $\bar{h}$ as well as low network cost.

1. Introduction

Wavelength division multiplexing (WDM) network provides a large number of high-speed (e.g., 1-Gbps) channels on a single optical fiber by transmitting multiple data streams in the form of independently modulating different wavelengths of light in the spectrum passed by a fiber.

This paper proposes a model to find an optimum logical topology in multihop WDM networks. The physical architecture of WDM networks is commonly configured as a broadcast-and-select, passive-star network [1] as shown in Figure 1. Three main components in this network configuration are (i) transceivers, which are transmitter (laser) and receiver (filter) for sending and receiving data, respectively, (ii) optical fiber as a medium for information transfer, and (iii) a star coupler, which combines all inputs from all nodes in the network, and broadcasts the mixed optical information to all outputs.

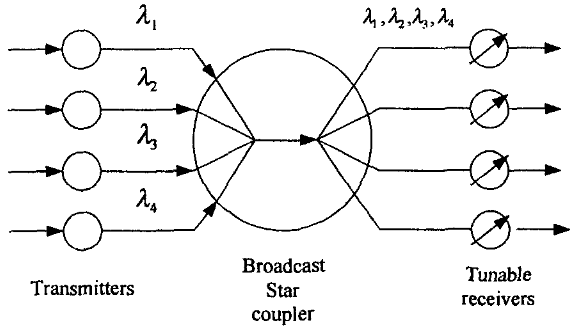

Figure 1. A broadcast-and-select, passive star WDM network.

In this paper, we concentrate on the broadcast-and-select, passive-star network in which we intend to search for the optimum regular logical topology. One important characteristic of a multihop WDM network is that the logical topology implemented is relatively independent on its physical topology. This means the logical topology of a WDM network can be changed and the node connecting pattern can be varied, while the physical topology of the network is kept fixed. This paper examines the following four regular topologies: ShuffleNet [2], de Bruijn graph [3], hypercube [4], and Manhattan street network (MSN) [5]. See Figure 2 for the structures of these topologies.

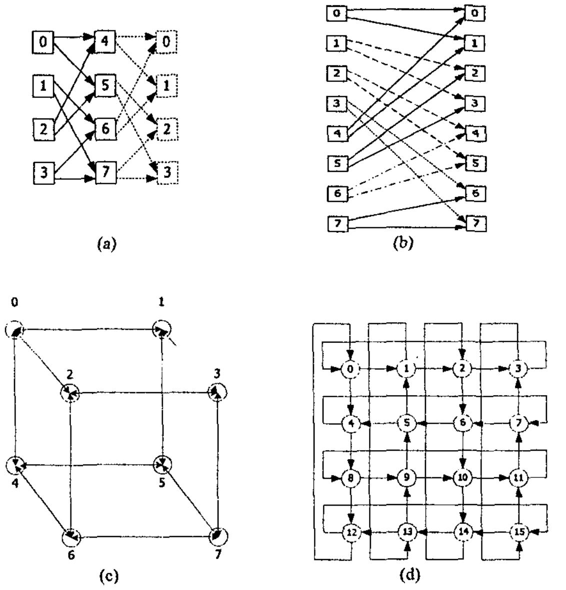

Figure 2. Regular network topologies: (a) a (2, 2) ShuffleNet, (b) a (2, 3) de Bruijn graph, (c) a hypercube network with 8 nodes and 12 bi-directional links, and (d) a 16-node MSN.

The rest of this paper is organized as follows. Section 2 describes a node placement problem and the formulation of the logical topology optimization problem using a new objective function. Section 3 gives the experimental results and discussion, where there are two steps to obtain the results. First, the minimum weight mean hop distance for each regular topology is determined by using a metaheuristic. Then the optimum logical topology based on the new objective function are investigated. Finally, Section 4 concludes this paper.

2. Logical Topology Optimization

2.1 Node Placement Problem

There are some research [4],[6] focused on the way to find optimum node placement pattern for placing array of nodes into an empty regular topology, where the traffic rate between all node-pairs are given. For example, let's consider the case of placing 8 nodes numbered from 0 to 7 into a $(2,2)$ ShuffleNet in Figure 2(a). This problem is called a node placement problem (NPP) [7], where the objective is to minimize the weight mean hop distance $\bar{h}$ between any node-pair. $\bar{h}$ is defined as

$$\bar{h} = \frac{1}{\Lambda}\sum_i\sum_j h_{ij}\cdot\lambda_{ij}, \tag{1}$$

where λ_{ij} is the traffic rate from node i to node j, $\Lambda = \sum_{i,j}\lambda_{ij}$ is the total traffic rate, and h_{ij} is the hop distance from node i to node j, which can be determined from the logical topology under consideration. For example, in the $(2,2)$ ShuffleNet, we can determine h_{ij} by counting the number of links connecting between each node-pair (from node i to node j) such as $h_{04} = 1$, $h_{02} = 2$, and $h_{06} = 3$. In Ref. [7], a heuristic algorithm called Lookahead Algorithm is proposed to solve the NPP by using the total traffic between any node-pairs as a node placement priority indicator. Although Lookahead Algorithm can give a solution to the NPP, it can be shown that the solution obtained is a local optimum. To find $\bar{h}$, this paper thus uses a metaheuristic called tabu search [8], since this method is capable in escaping from local optima.

In addition to the NPP, there are also some studies on the performance comparison of regular logical topologies. As an example, Ref. [9] compares the value of $\bar{h}$ in ShuffleNet and de Bruijn graph. The result is that, in a 32-node network, ShuffleNet with node degree $p = 4$ has lower $\bar{h}$ than de Bruijn graph with $p = 2$, while for 64-node network, de Bruijn graph with $p = 4$ has lower $\bar{h}$ than ShuffleNet with $p = 2$. Note that the node degree p is the number of transceivers at each node. For the topologies in Figure 2, we have p = 2, 2, 3, and 2, respectively. From the above comparison, it is clear that there is a trade-off between the node degree p and the weight mean hop distance $\bar{h}$. This means $\bar{h}$ can be simply decreased by increasing p.

2.2 Logical Topology Optimization Problem

As the objective function of the NPP is to minimize $\bar{h}$, we can select a regular configuration with large node degree p, and use it as the logical topology for WDM networks. However, this eventually increases the network cost, since more transmitters and receivers are needed to be installed at each node. As a consequence, we introduce a new objective function considering both $\bar{h}$ and the network cost, where we try to find the optimum logical topology that minimizes both of them simultaneously. The objective function X for a logical topology is then defined as follows.

$$X = \bar{h}\times D, \tag{2}$$

where D is the network cost, which can be separated into two parts, namely a fixed cost f, and a variable cost v.

In a WDM network, f can be considered as the cost of optical fiber and the star coupler, since these two components are independent on the logical topology used in the network. On the other hand, v is the cost of the transceivers, which can be varied for different topologies, and is obviously the function of p.

Although the cost function consists of two parts: f and v, the relationship between both of them is not clear, so we introduce a weighting parameter w and rewrite Eq. (2) as

$$X = \bar{h}\times(f + w\times v). \tag{3}$$

In Eq. (3), we consider the case of $v = kp^a \times N$, where N is number of nodes in the network, k is a constant equal to 10, and the cost index a is between $0 \le a \le 1$. Then the objective of our WDM network design problem is to find an optimum logical topology that minimizes X.

3. Experimental Results and Discussion

In the experiment, we determine the optimum logical topology, which gives minimum X, i.e., low $\bar{h}$ and low cost, for multihop WDM networks. We consider the number of user nodes n between 5 to 32. The traffic rate between each node-pair in the network is randomly set between 0 and 1. Then each of the logical topologies in Figure 2 are examined. In constructing a logical topology, we assume that the physical network has N nodes, where $N \ge n$. Note that there are some cases that N must be greater than n. For example, to use a ShuffleNet for $n = 5$, we need $N = 8$ as shown in Figure 2 (a). In other words, a 5-node ShuffleNet cannot be realized.

For each n, we generate ten random traffic patterns, each of which is applied to each regular topology. We then solve the NPPs by tabu search algorithm to find $\bar{h}$ of each problem.

Next, we consider the cost function D, which consists of fix cost f and variable cost v. For the value of f, we focus on the case that it is in the same order as v by setting it to be equal to the lowest v among the four regular topologies. The cost index a is varied as 0.1, 0.5, and 1, while the weighting parameter w is varied as 0.1, 1.0, and 10. For each case of the parameter, we calculate the fix cost f and variable cost v. Then, the network cost D and the objective function X are determined. Finally, we find the average value of X among the ten traffic patterns for each n. The numerical results are given in Table 1, 2, and 3. Note that LT is logical topology, Sh is ShuffleNet, MSN is Manhattan street network, deB is de Bruijn graph, and hyp is hypercube.

For $a = 0.1$, Table 1 shows that at $w = 0.1$ and n is between 5 and 24, hypercube has smaller X than other

Table 1. The average value of objective function X of regular topologies at $a = 0.1$

LT		5	8	12	16	20	24	27	32
$w = 0.1$	Sh	161.3	179.4	286.5	384.6	722.5	866.0	726.4	827.1
	MSN	161.3	179.4	326.4	499.0	929.8	883.3	1543.5	1780.2
	deB	157.3	188.8	328.3	493.7	559.4	670.0	784.5	685.7
	hyp	140.5	152.5	285.5	368.5	544.2	658.9	771.7	886.4
$w = 1$	Sh	293.4	326.2	635.1	747.6	1419.1	1574.6	1437.1	1547.8
	MSN	293.4	326.2	593.4	907.3	1690.5	1606.1	2962.9	3236.8
	deB	286.1	343.3	787.1	897.7	1180.1	1302.4	1426.4	1374.1
	hyp	259.9	282.1	606.9	689.6	1274.9	1415.1	1542.1	1674.3
$w = 10$	Sh	1613.8	1794.6	4119.8	4377.7	8385.6	8660.3	8544.3	8754.3
	MSN	1613.8	1794.6	3264.0	4990.5	9298.2	8833.5	17157.7	17802.7
	deB	1573.4	1888.6	4835.0	4937.5	7386.6	7629.3	7845.4	8258.6
	hyp	1453.1	1577.1	3826.3	3900.4	8581.9	8976.7	9244.9	9553.9

Table 2. The average value of objective function X of regular topologies at $a = 0.5$

LT		5	8	12	16	20	24	27	32
$w = 0.1$	Sh	212.9	236.8	387.1	516.8	953.2	1142.7	1109.7	1125.2
	MSN	212.9	236.8	430.7	658.5	1226.9	1165.5	2289.2	2349.1
	deB	207.6	249.2	504.4	651.5	754.2	900.4	1181.7	960.4
	hyp	188.5	204.6	391.8	501.3	765.5	918.6	1193.4	1220.7
$w = 1$	Sh	387.2	430.5	927.9	1080.2	1872.5	2077.7	2347.1	2379.9
	MSN	387.2	430.5	783.2	1197.2	2230.7	2119.2	4162.2	4217.1
	deB	377.5	453.1	1038.6	1184.5	1717.4	1881.8	2177.8	2370.2
	hyp	373.7	405.6	951.3	1060.3	2156.5	2358.1	2659.7	2720.7
$w = 10$	Sh	2129.5	2367.9	6335.6	6713.5	11064.8	11427.4	14721.5	14927.2
	MSN	2129.5	2367.9	4307.1	6584.9	12269.0	11655.8	22892.1	23490.8
	deB	2076.2	2492.0	6379.8	6515.1	11348.9	11695.6	12139.1	16467.3
	hyp	2225.5	2415.3	6546.3	6650.7	16066.6	16752.8	17323.4	17720.7

Table 3. The average value of objective function X of regular topologies at $a = 1.0$

LT		5	8	12	16	20	24	27	32
$w = 0.1$	Sh	301.1	334.8	566.6	750.9	1348.1	1616.1	1649.9	1673.0
	MSN	301.1	334.8	609.1	931.3	1735.1	1648.4	3237.4	3322.1
	deB	293.6	352.4	713.4	921.4	1100.7	1308.1	1706.4	1520.5
	hyp	273.2	296.5	590.6	745.4	1209.6	1430.6	1821.6	1863.4
$w = 1$	Sh	547.5	608.8	1503.3	1726.6	2648.1	2938.3	4124.8	4182.4
	MSN	547.5	608.8	1107.5	1693.2	3154.7	2997.1	5886.3	6040.2
	deB	533.8	640.7	1468.8	1675.2	2768.9	3007.9	3431.8	4973.6
	hyp	593.9	644.6	1709.6	1863.4	4320.0	4649.3	5100.5	5217.5
$w = 10$	Sh	3011.5	3348.8	10869.9	11483.9	15648.1	16160.8	28873.6	29276.9
	MSN	3011.5	3348.8	6091.0	9312.5	17351.0	16483.9	32374.4	33221.1
	deB	2936.2	3524.3	9022.5	9213.7	19451.1	20005.8	20685.2	39504.2
	hyp	3801.3	4125.5	12899.4	13044.1	35424.0	36836.9	37889.4	38758.4

topologies. The reason is that $\bar{h}$ is the dominant factor in X, while D is almost the same in all topologies. Thus, the optimum topology is the one that has small $\bar{h}$, or in other words large p. At $w = 1$ and $w = 10$, the hypercube has smallest X when n is between 5 to 16, except the case of $n = 12$ where MSN has smallest X. Note that for this case, MSN is the only topology that has $N = n$ that we can see in Table 4, while other topologies need $N > n$. When n is increased to be 20 and 32, de Bruijn graph has smaller X than other topologies. The reason is that $\bar{h}$ of de Bruijn graph smaller than ShuffleNet and MSN, or in the other words, de Bruijn graph has p more than both of them that we can see in Table 4.

Table 4. Comparison of the number of network nodes N and the node degree p for different number of user nodes n.

n	Logical Topology	N	p
5	ShuffleNet	8	2
	MSN	8	2
	de Bruijn graph	8	2
	hypercube	8	3
8	ShuffleNet	8	2
	MSN	8	2
	de Bruijn graph	8	2
	hypercube	8	3
12	ShuffleNet	18	3
	MSN	12	2
	de Bruijn graph	16	2
	hypercube	16	4
16	ShuffleNet	18	3
	MSN	16	2
	de Bruijn graph	16	2
	hypercube	16	4
20	ShuffleNet	24	2
	MSN	20	2
	de Bruijn graph	27	3
	hypercube	32	5
24	ShuffleNet	24	2
	MSN	24	2
	de Bruijn graph	27	3
	hypercube	32	5
27	ShuffleNet	32	4
	MSN	32	2
	de Bruijn graph	27	3
	hypercube	32	5
32	ShuffleNet	32	4
	MSN	32	2
	de Bruijn graph	36	6
	hypercube	32	5

When a is equal to 0.5, Table 2 shows that at $w = 0.1$, hypercube is not optimum except in the cases of $n = 5, 8$, and 16 where a increases from 0.1 to 0.5 that also increase in D of hypercube which has p more than other topologies. At $w = 1$, the result is the same as that in Table 1. When w increases to 10, ShuffleNet becomes the optimum logical topology for large n, except the case $n = 27$. This can be explained by the fact that ShuffleNet has smaller p than de Bruijn graph when n is large, except $n = 27$ where de Bruijn graph has smaller p.

At $a = 1$, we have that the variable cost v is a linear function of p. When $w = 0.1$ and 10, the result in Table 3 is the same as that in the previous table. Furthermore, the result of the case $w = 1$ is the same as that of the case $w = 10$.

4. Conclusion

In this paper, we formulate the logical topology optimization problem in multihop WDM networks based on a new objective function, which includes both the weight mean hop distance $\bar{h}$ and the network cost. The physical architecture of WDM networks is configured as a broadcast-and-select, passive-star network. There are four regular network configurations considered in this paper: ShuffleNet, de Bruijn graph, MSN, and hypercube. In the part of node placement problem, we find $\bar{h}$ by tabu search algorithm.

From the experimental results, hypercube is the optimum logical topology for the cases of small n and a. The reason is that $\bar{h}$ is the dominant factor in X for these cases. For large n and w, hypercube has larger X than other topologies because of the effect of the cost function. For large n with linear cost function ($a = 1.0$) and large w, we have that ShuffleNet is the optimum topology.

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