NETWORK DIMENSIONING IN WDM-BASED ALL-OPTICAL NETWORKS

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Abstract

The problem of network dimensioning, which involves the optimal network designs using minimal resources for a given well-predicted traffic between individual nodes but without a pre-determined network topology, is analyzed in details in this paper. Such optimal designs are critical, as the network resources are directly related to the cost of implementation. The problem complexity increases as the traffic between every node pair varies in a periodic manner. Furthermore, the presence of wavelength conflicts makes the network-dimensioning problem distinct and more complicated than the traditional circuit-switching networks. Here, we adopt the approach based on a multi-commodity flow problem. A general cost function covering the resources of all system components is formulated, and two solution approaches are presented; one based on integer programming and one on heuristics.

1. Introduction

Wavelength routing networks [1,2] that based on wavelength division multiple access (WDMA) has become one of the most viable architectures to achieve a scalable, high-capacity all-optical network with multiple access capability. Although suffering from complex architecture and management control, the wavelength routing network has many advantages over the simple broadcast-and-select network [3] architecture in wavelength utilization, where same wavelength can be used for multiple connections in spatially disjoint parts of the network. The concept of wavelength reuse not only can expand the network capability in its scalability in number of nodes and distances, the small limited number of wavelengths required relaxes the requirements on individual electro-optics components, making the all-optical network more realizable. Already, several large-scale WDMA testbeds are concurrently undertaking in U.S. [4,5], Europe [2], and Japan [6].

While there are substantial progress and studies on different aspects of WDMA wavelength routing network, the network dimensioning problem, i.e., how to maximize the use of the limited wavelength resources for different traffic patterns in different time segments, is not well understood. A core problem in network dimensioning is optical path assignment. Optical path assignment algorithms based on integer linear programming for standard wavelength-routing-network configuration were previously reported [7,8]. The network configuration of our interest is a variation of the standard wavelength routing network [1-6] with an intention to reduce the size of the wavelength cross-connects and improve the network efficiency. In addition, results derived from the network dimensioning analyses yield the essential information on optimal network planning. This can be translated to minimal network implementation cost.

Two solution approaches, one based on integer programming and the other based on heuristic, will be presented. In our analyses, the network is set in the planning stage, i.e., without a fixed network topology, and the only information available is the traffic patterns between nodes. Although both approaches can be applied to wavelength routing networks with and without wavelength conversions, we restrict our analyses for the latter configuration because the former is a simplified case of the latter [7]. Due to the immense complexity of the problem, only outlines of the solution are given for the integer programming based on a multi-commodity flow model. An algorithm based on minimum variance is established for the heuristic, and its results are compared with another heuristic based on shortest path. As will be discussed in the later section, the variance considered here refer to the usage among various wavelengths between any two connecting nodes. We show that the algorithm based on minimum variance performs considerably better than that provided by the shortest path by reducing the wavelength conflicts along various paths in the network. An illustrative example is also given for the comparisons of the two algorithms.

This paper is divided into the following sections. The wavelength routing network architecture is briefly outlined in Section 2. A detailed presentation of the network-dimensioning problem is given in Section 3. Both integer-programming and minimum-variance algorithm (heuristic) approaches are described in Section 4. Section 5 summaries this work.

2. Wavelength Routing Network Architecture

The wavelength-routing network consists of a set of switching nodes interconnected by fiber links composed of multiple single-mode optical fibers. In addition to the

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standard configuration where all input and output fibers are connected to the wavelength cross-connects (WCC) [9], we also consider a variation of this configuration where some input fibers are terminated directly at the destination nodes without going through the WCC. Thus, there are two types of fiber, transit fiber and direct fiber. Transit-fiber links terminate at the WCC, while direct-fiber links terminate at the receiver module [10] of the destination node. Wavelength signals can also be directly sent from the transmitter module [11] to the WCC of the adjacent nodes. The main advantage of direct fiber links is a reduction in the dimension or the complexity of the WCC[1]. The node architecture is given in Fig. 1. As shown in the figure, signals carried by various wavelengths $\lambda_i ... \lambda_m$ in transit fibers are switched and routed by a WCC to specific outgoing fiber links. Any switching between a transit fiber to a direct fiber can be assisted by an optical relay which serves as hybrid between direct and transit fibers.

Optical connections between any two nodes are formed by a set of concatenated common wavelengths, or *lightpaths*, between the nodes.

3. Network Dimensioning Problem

The traffic pattern in a network is usually periodic in nature. Within a certain period, we can divide the time into contiguous segments such that the traffic in each segment is approximately constant. A typical period could be a 24-hour day or a seven-day week. Assuming we are free from a given network topology (e.g. network planning), the network dimensioning problem can then be stated as follows: for a given set of traffic patterns(one for each time segment), determine the lightpath assignments for different time segments such that utilized resources are kept at the minimum. The network resources include wavelength channels, optical fibers, optical amplifiers, wavelength cross-connects, fixed tuned transmitters and fixed tuned receivers, optical relays, and other components necessary in the network, all of which can be translated to the system implementation cost. The complexity of this problem can be reduced by solving the two following inter-connecting problems:

1. Optical path assignment for different traffic patterns on different time segments;
2. Optical fiber required to be installed between adjacent nodes.

The lightpath assignment is further complicated by the presence of wavelength conflict, which occurs when there is no common wavelengths available along all paths connecting the source and destination nodes. This wavelength conflict problem can be resolved for networks with wavelength conversion, which is a simplified case of the network without the conversion capability.

[1] For w incoming fibers consisting of w1 transit and w2 direct fibers (w1+w2=w), the dimension of the WCC in our proposed configuration is $w1^2$, instead of $(w1+w2)^2$ of the standard configuration.

4 Two Solution Approaches

4.1 Integer Program Formulation

Let $N=\{1, 2, 3, \cdots, n\}$ be the set of switching nodes. To facilitate the representation of the transit fiber links and direct fiber links to be set up in the network, an augmented network model is created by incorporating a set of conjugate nodes $N^* = \{n+1, n+2, ...2n\}$, where the conjugate node of node i is denoted as node $n+i$. Conjugate nodes are used as the termination points of direct fiber links whereas regular switching nodes are those connected by transit fiber links.

The augmented network allows us to conveniently formulate the network-dimensioning problem as a multi-commodity-flow problem. To see this, we may think of the m different wavelengths carried in each fiber used for the network as m types of commodities. Establishing a lightpath from node s to node t using wavelength λ_k is equivalent to sending one unit of type k commodity from node s to node t. To establish d_{st} lightpaths is equivalent to sending d_{st} commodities from node s to node t, where these d_{st} commodities can be of any combinations of these m commodity types as long as the total is d_{st}.

To develop the mathematical model, we first define $X^k_{ij,st}(h)$ as the number of wavelength λ_k used (can be carried by multiple fibers) from node i to adjacent node j while establishing lightpaths between the source node s and the destination node t in time segment h. The set of variables of number of wavelengths, $\{X^k_{ij,st}(h)\}$, has to satisfy the following constraints, denoted by ψ.

1. $$\sum_{k=1}^{m} \sum_{\substack{i=1 \\ i \neq t-n}}^{n} X^k_{it,st}(h) \geq d_{st}(h)$$

2. $$\sum_{k=1}^{m} \sum_{\substack{i=1 \\ i \neq s}}^{2n} X^k_{si,st}(h) \geq d_{st}(h)$$

3. $$\sum_{\substack{l=1 \\ l \neq s}}^{2n} X^k_{il,st}(h) = \sum_{\substack{l=1 \\ l \neq s}}^{n} X^k_{li,st}(h)$$

4. $$X^k_{ij,st}(h) = 0$$

$$\forall n+1 \leq j \leq 2n \ and \ j \neq t, i \in N, 1 \leq k \leq m$$

5. $X^k_{ij,st}(h)$ is a non-negative integer

$$where \quad s \in N, \quad t \in N^* \quad and \quad 1 \leq h \leq H$$

These constraints can be interpreted as below:

Constraint 1 states that in time segment *h*, the total number of wavelengths assigned to a source-destination pair *(s,t)* on all direct fiber links terminating at the receiver modules of node *t* should be greater than or equal to $d_{st}(h)$, the required number of lightpaths between node *s* and node *t* in time segment *h*.

Constraint 2 states that for a source-destination pair *(s,t)*, the total number of assigned wavelengths on all output fiber links of node *s* should be greater than or equal to $d_{st}(h)$.

Constraint 3 states that on a transit node, the number of input λ_k wavelengths assigned for a source-destination node pair *(s,t)* should be the same as that of the output.

Constraint 4 states that no wavelength will be assigned for a node pair *(s,t)* on direct fiber links other than those originating from node *s* and ending in node *t*.

We are then ready to derive the fiber link requirements of the network in terms of $\{X^k_{ij,st}(h)\}$. For any set $\{X^k_{ij,st}(h)\}$ satisfying constraint set ψ, i.e. for any lightpath connection plan satisfying $\{D(h)\}$, the number of wavelength λ_k, F_{ij}^k, used for establishing lightpaths between adjacent nodes *i* and *j* is given by

$$F_{ij}^k = \underset{h}{Max}\left\{\sum_{(s,t)\in\Omega_{ij}} X^k_{ij,st}(h)\right\} 1\le i\le n, 1\le j\le 2n,$$
$$i\ne j, 1\le k\le m$$

where $\Omega_{ij} = \{(s,t) \mid s\in N,\ t\in N^*,\ s\ne j,\ t\ne i,\ t\ne n+s\}$.

The number of fiber links L_{ij} needed between nodes *i* and *j* is thus

$$L_{ij} = \underset{k}{Max}\{F_{ij}^k\}$$

We are then ready to formulate the minimum required transmitter and receiver modules for each node. For a given node *i*, the number of transmitter modules S_i needed (number of local fiber link inputs to the WCC plus the number of direct out fibers, see Fig. 1) for satisfying $\{D(h)\}$ is given by

$$S_i = \underset{k}{Max}\left\{\underset{k}{Max}\left\{\sum_{j=1}^{2n}\sum_{t=n+1}^{2n} X^k_{ij,st}(h)\right\}\right\}$$

where, $i\in N, 1\le k\le m, 1\le h\le H$.

The number of transit fiber links, T_i, passing through node *i* is

$$T_i = \sum_{\substack{k=1\\k\ne i}}^{n} L_{ki} \qquad i\in N$$

The number of direct fiber links R_i terminating at node *i* equals to the number of receiver modules required, and is given by

$$R_i = \sum_{\substack{k=1\\k\ne i}}^{n} L_{ki} \qquad i\in N^*.$$

The total number of outgoing transit and direct fiber links O_i is

$$O_i = \sum_{\substack{k=1\\k\ne i,k\ne i+n}}^{2n} L_{ik} \qquad i\in N.$$

The dimension of the WCC is then $(S_i+T_i)\times O_i$ in order to satisfy $\{D(h)\}$.

The objective function *Z* to achieve minimal network resources consists of fiber-link cost $C_L^{(ij)}(n)$ linking between node pair *(i,j)* for node *n*, WCC cost $C_S(S_i+T_i, O_i)$, transmitter-module cost C_T, receiver-module cost C_R, and optical amplifier cost C_A. Note that the installation component in fiber link cost is substantially large comparing to the total cost at each installation. The objective function is to minimize *Z*, which is the sum of the cost function, subjected to constraint set ψ.

$$Minimize\ Z = \sum_{i=1}^{n}\sum_{\substack{j=1\\j\ne i,j\ne i+n}}^{2n}\left\{C_L^{(ij)}(L_{ij}) + L_{ij}C_A\right\}$$
$$+\sum_{i=1}^{n} C_S(S_i+T_i) + \sum_{i=1}^{n} S_iC_T + \sum_{i=n+1}^{2n} R_iC_R$$

Unfortunately, the exact solution of the above nonlinear optimization problem is formidable even for very small size networks.

4.2 Heuristic Approach

4.2.1 Minimum Variance Algorithm (MVA)

The total number of routes R_o is an exponential function of the number of nodes *n* in the network. To start with, we choose $R_o\le\alpha$ between any node pair. The total number of the candidate routes is then restricted to no more than $\alpha n(n-1)$ for an *n*-node network. Let us denote this set of candidate routes as *R*.

For a given source and destination node pair *(s,t)* with traffic matrices *D(h)*, we begin by putting an optical fiber between each connecting node pair for every possible route connecting *(s,t)*. The total fiber-link cost is calculated for each of these routes. For as long as $D(h)_{mn}>0$, we will keep on assigning lightpaths with unused wavelengths connecting the *(s,t)* by applying the Minimum Variance Subroutine (MVS) as described in 4.2.2. For each possible route, the average cost of setting up a lightpath is then evaluated by dividing the total cost of fiber links on that route with the number of lightpaths that can be established by the subroutine. We then choose the route that yields minimum average cost. This procedure is repeated until demands in all time segments *{D(h)}* are satisfied. The following is the pseudo code for MVA.

Repeat

{1. For each $r \in \Re$,

{

a) Increase the number of fiber links along each segment of r *by one,*

$$L_{ij}^{\#} = L_{ij} + 1 \qquad \text{if segment } (i,j) \in r$$

Calculate the incremental cost , ΔZ *, for adding the fiber links on route r as*

$$\Delta Z = Z\left(L_{ij}^{\#}\right) - Z\left(L_{ij}\right)$$

b) Apply MVS with $\{X_{ij,st}^{k}(h)\}$, $\{L_{ij}^{\#}\}$ *and* $\{e_{st}(h)\}$ *as input to obtain an updated lightpath assignment plan.*

c) Add up the number of new lightpaths established in all time segments from the wavelength assignment plan and denote it by u.

d) Calculate the cost per lightpath, $c = u^{-1}\Delta Z$

}

2. Denote the route that gives minimum c as r^*

3. Update the link count on r^*,

$L_{ij} \leftarrow L_{ij} + 1$ *if* $(i,j) \in r^*$, *the cost*

$Z = Z + \Delta Z|_{r^*}$ *and* $\{X_{ij,st}^{k}(h)\}$, $\{e_{st}(h)\}$ *based on the lightpath assignment plan for* r^*.

4. Identify all source-destination node pairs that have their lightpath requirements satisfied, i.e. those (s,t) pairs with $e_{st}(h)=0$, $1 \le h \le H$ *and denote them by the set of Y.*

5. Remove all routes belonging to Y from R.

} Until all $e_{st}(h)=0$.

4.2.2 Minimum Variance Subroutine (MVS)

The wavelength utilization profile of the fiber links between all adjacent node pair *(i,j)* in time segment *h* is given by $\{X_{ij}^{k}(h)\}$ where $X_{ij}^{k}(h)$ is the number of assigned lightpaths between *(i,j)* using $\bullet_k$ in time segment *h*, and $1 \le k \le m$. $X_{ij}^{k}(h)$ equals to

$$X_{ij}^{k}(h) = \sum_{s=1}^{n} \sum_{t=n+1}^{2n} X_{ij,st}^{k}(h)$$

where $X_{ij,st}^{k}(h)$ equals to $X_{ij}^{k}(h)$ under the constraint that the source and terminal node pair must be *(s,t)*.

The variance of the wavelength utilization profile, $V(r_{st},k,h)$, is then

$$V(r_{st},k,h) = \sum_{(i,j)\in r_{st}} \left\{ \sum_{\substack{l=1 \\ l\neq k}}^{m} \left(X_{ij}^{l}(h) - \overline{X_{ij}(h)}\right)^2 + \left(X_{ij}^{k}(h) + 1 - \overline{X_{ij}(h)}\right)^2 \right\}$$

with respect to k *and* r_{st}. Here,

$\overline{X_{ij}(h)} = m^{-1}\left(1 + \sum_{k=1}^{m} X_{ij}^{k}(h)\right)$ is the mean of wavelength utilization on link segment *(i,j)* in time segment *h* for every new lightpath assigned. This variance function is the measure for the uniformity of wavelength utilization in the network. It can be argued that the more uniform the profile, the fewer the chance the wavelength conflict occurs, thus requiring fewer number of fiber links established between nodes. Feasible route has a common set of free wavelengths on all its links of the route and can be expressed mathematically as:

$$X_{i,j}^{k}(h) + 1 \le L_{ij}^{\#}$$

for all link segment (i,j) on every possible route.

R_{st} is the set of all feasible routes for node pair *(s,t)*. We then extend the search for all possible *(s,t)* and λ_k, and determine the route with minimum variance denoted by $f_{st}(h)$. This process continues until no more lightpath can be setup in any time segments.

The following is the pseudo code for the *MV* subroutine:

Input: $\{L_{ij}^{\#}\}$ *Fiber links Count between node i and node j*

$\{X_{ij,st}^{k}(h)\}$ *Lightpath connection plans*

$\{e_{st}(h)\}$ *Unsatisfied lightpath numbers between nodes s and t*

for $1 \le h \le H$ *do {*

Construct U as the set of source-destination node pairs with $d_{st}(h) > 0$

Repeat{

for every node pair (s,t) in U do {

Construct R_{st} *the set of all feasible routes for node pair (s,t).*

For a non-empty R_{st} *, obtain*

$$f_{st}(h) = \min_{\forall r_{st}\in R_{st}} \left\{ \min_{1\le k\le m} \{V(r_{st},k,h)\} \right\}$$

and the corresponding k and r_{st} *values*

}

Select the node pair that has minimum $f_{st}(h)$ *for establishing a new lightpath using the corresponding* λ_k *and* r_{st}. *If the lightpath requirements for this node pair are satisfied, remove it from U.*

Update $\{X_{ij,st}^{k}(h)\}$ *and* $\{e_{st}(h)\}$.

} *until no more feasible routes exist for all node pairs*

}

4.2.3 Shortest Path Algorithm (SPA)

In order to demonstrate how the MVA can maximize the wavelength utilization in an optical network, we compare it to another algorithm based on shortest path. Being itself also a greedy algorithm, the SPA pseudo codes are similar to that of the MVA. It establishes the lightpath based on the shortest distance between the source and destination. Using SPA, the cost of setting up a lightpath is proportional to the sum of the costs of fiber installation including all the links that the lightpath transverses. Since the cost of installing fibers is largely proportional to the distance between two nodes, the lightpath with the shortest distance also yields a local minimum cost.

4.3 Performance Comparisons

We assume 9 nodes are to be interconnected to form an optical backbone. There are altogether three cost matrices *C1*, *C2* and *C3*. The traffic loads of the demand matrices vary from 200 to 3000, where the loads are defined as the total number of lightpaths required to be set up over the network. The number of wavelengths in the fibers, m, is taken to be 4, 8 or 16. The range of traffic demands (number of lightpath) and normalized fiber installation costs between any node pair is between 0 and 10. The number of time segments H is taken to be 3. Figure 2 shows the normalized cost as a function of the traffic load predicted by the MVA and SPA for $m = 4$, 8 and 16 and using cost matrix *C1*. In general, both MVA and SPA give a linear increase in cost as the traffic demand increases. Also, the cost decreases as m increases. Over the range of traffic load studied, the projected cost calculated by MVA is uniformly lower than that predicted by SPA. Similar results are obtained for different cost matrices *C2* and *C3*.

Table 1 further compares the two algorithms by evaluating the ratio of the average projected costs q, q = (average projected cost by MVA)/(average projected cost by SPA), for different cost matrices and number of wavelength. The average cost is generated over different traffic matrices. In general, q decreases as m increases. The results are similar to those obtained in Fig. 2.

For a given traffic matrix, the costs predicted by both MVA and SPA differ substantially. The much larger cost projection by SPA over MVA (20%-60% see Table 1) suggests that the total number of installed fibers is also larger in the SPA case. Consequently, the maximum network capacity scales accordingly, even though the number of request lightpath remains the same for both cases. This also implies that there are more unused wavelengths in the lightpath assignment generated by SPA. We can therefore argue that the wavelength conflict is more serious in the lightpath assignment generated by SPA than that from MVA.

We further investigate how the projected cost changes as wavelength increases for a given fixed number of installed optical fibers. Here, we only consider the case in which the cost is predicted by MVA, since we have already demonstrated MVA is superior than SPA. As the number of wavelength, or lightpath, doubles, the traffic capacity of the optical network will also double. Conversely, the fiber installation cost will be reduced by a maximum of 50% under the same traffic load. This effect is demonstrated in Table 2, showing that the projected cost by MVA (about 30-40% cost reduction) using the cost matrix *C1*. Similar results are obtained for cost matrices *C2* and *C3*.

5. Summary

This paper studies the network-dimensioning problem for an all-optical wavelength routing network. Two solution approaches, one based on integer programming and the other based on heuristic, are presented. Solutions of the integer-programming approach should yield a configuration with minimum implementation cost. Due to the immense complexity of the problem, only outlines of the solution are given for the integer programming based on a multi-commodity flow model. An algorithm based on minimum variance is established for the heuristic, and its results are compared with another heuristic based on shortest path. We show that the algorithm based on minimum variance performs considerably better than that provided by the shortest path by reducing the wavelength conflicts along various paths in the network.

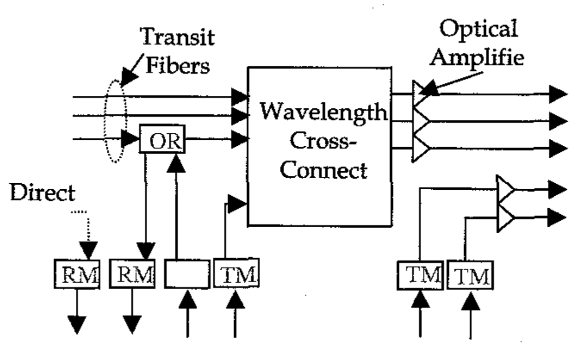

Figure 1. Proposed node architecture. TM is fixed-tuned transmitter module and RM is fixed-tuned receiver module, and OR is the optical relay.

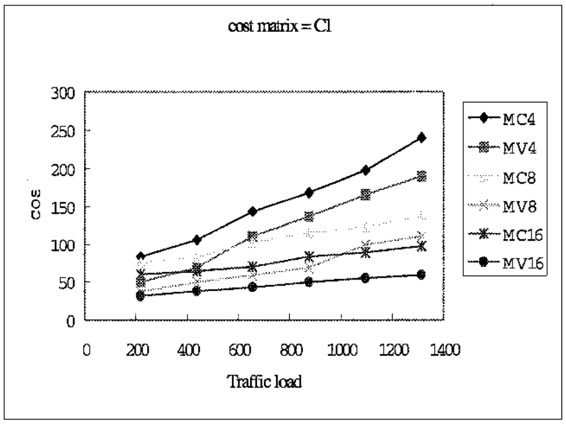

Figure 2. Network installation cost versus traffic load using cost matrix *C1*.

Number of Wavelength	C1	C2	C3
4	0.743923	0.494199	0.821689
8	0.646571	0.454908	0.779649
16	0.587841	0.448158	0.756901

Table 1. The average cost ratio for different combinations of cost matrices and wavelength numbers.

Wavelength No. Traffic loads	4	8	16
1200	110.6	66.5	44
1500	132.6	77.3	51.2
1800	155	89.3	56.2

Table 2: Assignment results for different combinations of wavelength numbers and traffic loads using cost matrix *C1*.

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