On the Robustness of Planning Methods for Traffic Changes in WDM Networks

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Many conventional planning and/or designing scheme of WDM networks assume that the future traffic demand is known beforehand. However, it is difficult to predict the future traffic demand accurately in a practical sense. In this paper, we develop a scheme to design a WDM network that would accommodate as much traffic as possible against a variety of traffic patterns, that is, a WDM network robust against traffic uncertainties. Our basic idea is to select a node–pair that is expected to be a bottleneck in the future, and then to deploy network equipments so that the volume of traffic accommodated by the node–pair increases. The results in our simulation show that the WDM network designed by our method can accommodate more traffic demand than those designed by the existing methods with the same cost.

OCIS codes: 060.0060, 060.4250.

1. Introduction

Wavelength division multiplexing (WDM) networks are emerging as a practical solution to provide an infrastructure for the next generation Internet. When a traffic demand occurs between a source–destination pair in a WDM network, a lightpath, where signals are handled optically at intermediate nodes, is configured to transport the traffic. At each intermediate node, an optical cross–connect (OXC) switches the wavelengths of each input port to appropriate output ports.

Various design methods for minimizing the cost of the physical network in a single design period, of which all equipments are installed at the beginning have been studied [1, 2, 3]. Planning in a single design period is to design the network that can accommodate traffic demand occurring during the period. In those studies, they design the WDM networks based on an explicit knowledge of the traffic demand (e.g., a typical traffic demand occurring during the period). While we may be able to estimate total traffic demand in the near future (e. g., Internet traffic doubles each year [4]), in practice, it is difficult to predict traffic pattern of each source–destination pair, because the advent of popular World Wide Web servers or data centers has drastically affected traffic demand and traffic pattern. More significantly, there are various types of data traffic such as video streams and P2P traffic with different traffic characteristics, which introduce several traffic patterns during the period. Therefore, conventional design methods using a single traffic pattern are inadequate to deal with the unpredictable traffic.

In this paper, we propose a scheme for designing WDM networks that focus on the robustness against traffic changes. Here, we consider a network is robust when the network accommodates a variety of traffic patterns. Our basic idea is to design a network accommodating several predicted traffic patterns that follow a certain distribution such as normal or exponential distribution. For each traffic pattern, we select node–pairs that become the bottleneck in accommodating the traffic and deploy network equipments for the node–pairs. By examining various traffic patterns, we expect that nodes that are likely to be the bottleneck get more equipments while nodes that are less likely to be the bottleneck get less equipments, which leads to constructing robust and cost–effective networks. Note that a real problem is that we have no ways of knowing which distribution the traffic will follow. In this paper, we simply assume that the discrepancy between the volume of traffic actually occurring and the predicted volume will follow a normal distribution. However, our method allows general distributions for discrepancy.

Our design method incrementally extends the size of OXCs and leases dark fibers until the designed network has the ability to accommodate a variety of traffic patterns. We handle the incremental operations based on the ADD algorithm to which we modify the traditional ADD algorithm [5]. The ADD algorithm addresses two design problems of robust networks; the *OXC–deployment problem* and the *fiber–deployment problem*. The *OXC–deployment problem* involves determining how many ports of each OXC are needed to design a robust WDM network. In this problem, we first identify the node-pair with bottleneck, which is determined by obtaining the *maximum flow value* of each node–pair. Then, we upgrade an OXC on a node so that upgrading it leads to maximizing the maximum flow value of the node-pair with bottleneck. We also try to design a robust WDM network based on the maximum flow value in the *fiber–deployment problem*, in which a number of dark fibers are leased. We determine where to set up lightpaths and where to lease optical fibers. There are various routing algorithms that determine the route of lightpaths. For instance, we may be able to accommodate as much traffic demand as possible without a priori knowledge of future traffic demand by utilizing MIRA (Minimum Interference Routing Algorithm) [6] and MOCA (Maximum Open Capacity Routing Algorithm) [7]. However, these two algorithms need physical topology as an input parameter and we cannot directly utilize them in our fiber–deployment problem, because the physical topology is not input information but output information in our problem. Thus, we also propose a routing and fiber/wavelength assignment algorithm that we call EMIRA (Enhanced Minimum Interference Routing Algorithm).

This paper is organized as follows. In Section 2, we describe our WDM network model and refer to the planning of robust WDM networks. In Section 3, we explain our scheme to design robust WDM networks. In Sections 4, we show the numerical results obtained through simulations and evaluate the proposed scheme. In Section 5, we present our conclusions and directions for future work. The explanation of MIRA, a routing algorithm that our EMIRA is based on is given in the Appendix.

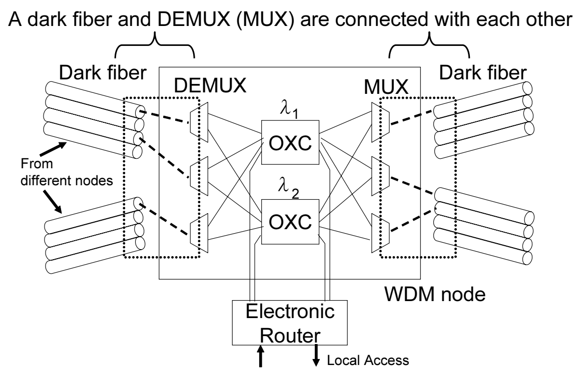

Fig. 1. WDM node architecture

2. Planning and Designing a Robust WDM Network against Traffic Changes

2.A. Modeling a WDM Network

Our WDM network model consists of both physical and logical topologies. The WDM physical topology is the actual network which consists of WDM nodes, WDM transmission links, and electronic routers. Each WDM node equips with MUXs/DEMUXs (multiplexers and demultiplexers) and OXCs as depicted in Fig. 1. The incoming multiplexed signals are divided into each wavelength at a DEMUX. Then, each wavelength is routed to an OXC. The OXC switches the incoming wavelength to the corresponding output port. Finally, wavelengths routed to a MUX are multiplexed and transmitted to the next node. An OXC also switches wavelength from/to electronic routers to provide add/drop functions. We do not consider waveband switching [8] which decreases the number of OXCs. Wavelength conversion is not allowed at WDM nodes. As illustrated in Fig. 1, the number of optical fibers between two WDM nodes (optical fibers connected to MUXs/DEMUXs) may not be identical.

We intend our network design method for WDM lightpath networks, where each traffic demand is accommodated on a lightpath. A lightpath is composed of a sequence of WDM channels, connecting the source electronic router to the destination one. After we design the WDM physical topology with the scheme we propose, we set up lightpaths for traffic demand in node–pairs. We call a set of lightpaths the *logical topology*.

2.B. Planning a WDM Network

As we mentioned, we will design a WDM network robust against traffic changes. Our design scheme can be utilized by network designers (e.g. service providers) who deploy WDM nodes by themselves and lease dark fibers from carriers. Since the network designers are likely to decrease equipment cost, we use minimum size (in terms of the number of ports) of OXCs at WDM nodes and a minimum number of optical fibers in links to design a robust WDM network. In doing so, we develop incremental approach, which will be described in Section 3. Initially, we prepare small size OXCs and candidate fiber locations (i.e., links) for our design. The dark fibers are connected to available DEMUXs/MUXs as long as there are available ports at the OXC. The connection of dark fibers are allowed on the candidate fiber locations but the number of dark fibers to be leased is not limited. As for OXCs, we use OXCs with the discrete number of ports (e.g., 4×4, 8×8, and 16×16 OXCs). We assume that the number of multiplexed wavelengths is identical among all optical fibers.

We introduce the following restrictions on how to deploy OXCs to simplify maintenance for the network operator.

- We deploy one non-blocking OXC for each wavelength on each WDM node. For instance, when we require OXC with 8 ports to establish 8 lightpaths for each wavelength, we deploy an 8×8 OXC instead of two 4×4 OXCs. As a result, we can decrease the number of OXCs which the operators should maintain.

- We make the number of OXC ports for each wavelength on a WDM node identical. When we increase the number of OXC ports for a wavelength, we also add the same number of ports for the other wavelengths on the node.

2.C. Modeling Traffic Changes

Conventional design methods for WDM networks assume that traffic demand is predictable. However, in practice, because it is very difficult to precisely predict what this will be in the future, we should design a network that can accommodate this expected demand without getting involved with precise predictions. One promising way to design such a network is to deploy redundant resources to all links and nodes, that is, to introduce excess resources $X\%$ more than the required quantity. However, this approach tends to result in high–cost networks since overall traffic demand seldom exceeds the predicted demand.

Instead of preparing redundant resources, we try to design a network accommodating several predicted traffic patterns that follow a certain distribution, such as normal or exponential distribution. A real problem is that we have no ways of knowing which distribution the traffic will follow. We assume that the discrepancy between the volume of traffic actually occurring and the predicted volume will follow a normal distribution. Then we design a robust network based on this assumption by ensuring that the designed network will accommodate the traffic change that follows this distribution. Here, we define the traffic change as the error between predicted traffic volume and the volume of the traffic actually occurring. Note that, in this paper, "traffic change" does not refer to the change of traffic demand in a short time; for example, the difference between the volume of traffic in day-time and the volume of traffic at night.

Our scheme generates a set of traffic demand based on a predicted traffic with prediction error assumed to follow a normal distribution in the current paper, and utilizes it as an input parameter of the WDM network design problem. Each traffic demand is expressed as a traffic matrix. The traffic matrix consists of the volume of traffic demand each node–pair requests ($\boldsymbol{T} = \{t_{ij}\}$). Given μ_{ij}, the average volume of traffic that node–pair (i, j) in a predicted traffic matrix requests, and σ_{ij}, the standard deviation which determines how much the traffic changes, our method generates $(K-1)$ traffic matrices ($\boldsymbol{T}_k = \{t^k_{ij}\},\ k = 1, 2, \ldots, K-1$). t^k_{ij} is a value of the random variable that follows a normal distribution $N(\mu_{ij}, (\sigma_{ij})^2)$. $\boldsymbol{T}_0 = \{\mu_{ij}\}$ and $\boldsymbol{\Sigma} = \{\sigma_{ij}\}$ are input parameters of the network design problem. $\boldsymbol{T}_0$ expresses the predicted traffic demand. $\boldsymbol{\Sigma}$ is a matrix consisting of σ_{ij}. The values for σ_{ij} will be selected based on the statistical measurement of the traffic change in the past and the network designer's judgment. However, how we should select those values is out of scope of this paper.

Our method defines the condition robust WDM networks need to fulfill to individually accommodate all the K traffic matrices, which consists of $(K-1)$ generated traffic matrices and the predicted traffic matrix. This condition is called RTC (Robustness against Traffic Changes). Networks with RTC can accommodate traffic matrices changing within the range specified by $\boldsymbol{\Sigma}$ and K. When the traffic change does not actually follow a normal distribution, we believe that our method can accommodate the traffic demand by utilizing the obtained distribution as input information instead of a normal distribution.

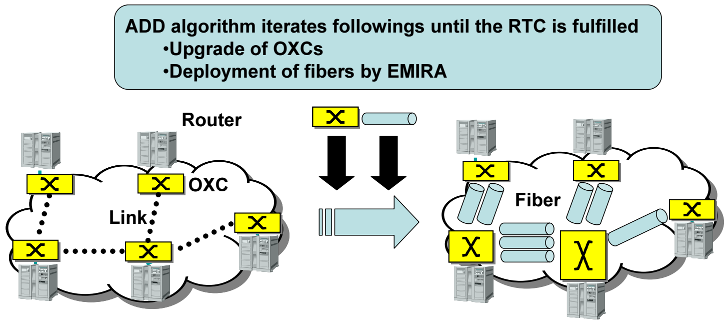

Fig. 2. Outline of WDM network design

3. WDM Network Design Method Robust against Traffic Changes

3.A. Outline of Proposed Design Method

In our design method, we deploy optical components (i.e., OXCs and fibers) until the designed network fulfills the RTC requirement. The design method includes the following two problems. We handle them repeatedly by using the ADD algorithm (See Fig. 2).

1. OXC–deployment problem: Given the expected traffic demand and a WDM physical topology, we determine how many ports of each OXC are needed to design a robust network. To achieve this, we first find the node-pair that limits the traffic volume accommodated by the network. We then determine the OXC port count needed on a node so that the traffic volume to be accommodated is maximized.

2. Fiber–deployment problem: Given the expected traffic demand and the WDM physical topology including the new OXCs in the OXC–deployment problem, we determine where and how many fibers to lease. To achieve this, we propose EMIRA algorithm. Its objective is to deploy optical fibers to maximize the volume of accommodated traffic. Note that our EMIRA adds a fiber only when there are sufficient OXC ports.

The traditional ADD algorithm was proposed to resolve the warehouse deployment problem [5]. In the traditional algorithm, the iteration of adding a warehouse is continued until the addition offers cost savings less than a given value. In our ADD algorithm, we find two main differences from the traditional one. The first is the condition to end the iteration. Iterations are stopped when the designed network can individually accommodate all the K traffic patterns. The other is a pointer to add resources during the iteration. We select the node to be upgraded on the basis that the maximum flow value of the bottleneck node–pair is increased to the highest possible level. The maximum flow value of a source–destination pair means an upper bound for the total amount of available bandwidth (the number of lightpaths in our case) that the node–pair will be able to accommodate by utilizing the remaining resources. The bottleneck node–pair is defined as the one whose ratio of the maximum flow value to the volume of traffic demand is lowest (See Section 3.2).

Our solution approach to the network design problem is as follows.

INPUT

$\boldsymbol{G}_{(x-1)}$: WDM physical topology designed during the previous period (the $(x-1)$ th period).

$\alpha^{(x)}$: Expected traffic growth rate from the previous design period.

$\boldsymbol{M}^{(x-1)}$: A matrix each element of which represents expected volume of traffic demand in the previous period, $\mu_{ij}^{(x-1)}$.

$\boldsymbol{\Sigma}^{(x)}$: A matrix each element of which represents a standard deviation, $\sigma_{ij}^{(x)}$. It determines how the traffic demands between nodes i and j change during period x. A different standard deviation for every node–pair can be inputted.

K : Number of traffic matrices used to design a robust WDM network.

p : Number of OXC ports initially placed on each node.

δ : Number of increased ports when a new OXC is upgraded.

OUTPUT

WDM physical topology that fulfills the RTC requirement during this period.

DESIGN METHOD

Step (1): Calculate K traffic matrices as follows.

Step (1-a): Generate a traffic matrix, $T_0 = \{\mu_{ij}^{(x)}\}$, based on a predicted traffic demand, where $\mu_{ij}^{(x)} = \alpha^{(x)} \times \mu_{ij}^{(x-1)}$.

Step (1-b): Based on T_0, generate $(K-1)$ traffic matrices ($T_1, \ldots, T_{K-1}$). Each element t_{ij}^k $(1 \leq k \leq K-1)$ follows a normal distribution $N(\mu_{ij}^{(x)}, (\sigma_{ij}^{(x)})^2)$.

Step (2): Install a $p \times p$ OXC for each wavelength at each node. We refer to the installed OXC as an upgradable OXC. They are added to a topology designed in $(x-1)$th period $\boldsymbol{G_{x-1}}$.

Step (3): Apply ADD algorithm. Namely, repeat following steps until RTC is satisfied.

Step (3-a): Increase the number of ports of upgradable OXCs by δ at node n that is a bottleneck of the traffic volume accommodated by the network. In Section 3.B, we describe how to select node n in detail.

Step (3-b): Lease fibers. Input K traffic patterns from T_0 through T_{K-1} and try to accommodate traffic demand that have not been accommodated in the previous iteration yet by using EMIRA (see Section 3.C). Set b_k to the number of lightpaths that cannot be accommodated when the traffic pattern is T_k.

Step (3-c): If the total number of blocked lightpaths ($\sum_{k=0}^{K-1} b_k$) is greater than 0, go back to Step (3-a) and try to upgrade OXCs. Otherwise finish the designing the network.

In Step (1), we roughly predict traffic pattern $\boldsymbol{T}_0$ assuming that the traffic increases at a regular rate [4]. Then we generate $(K-1)$ traffic patterns ($T_1, \ldots, T_{K-1}$). In Step (2), we install a $p \times p$ non–blocking OXC for each wavelength on nodes. On the node that is short of ports, increase the number of ports using the following steps. In Step (3), we apply our ADD algorithm. A WDM network can be designed by repeating Steps (3-a) through (3-c) until all the K traffic patterns are individually accommodated. In Step (3-a), we upgrade the OXCs on the target node. Since one OXC is prepared to each wavelength (see Fig. 1), we simultaneously upgrade all the OXCs on the node. As a result, we can keep the numbers of ports of the OXCs on the node identical regardless of wavelength. We regard the designed WDM network that accommodates all the traffic patterns generated in Step (1) as a robust one.

3.B. Scheme for the OXC–Deployment Problem

The objective of the OXC–deployment problem is to determine that how many ports of each OXC are needed to design a robust WDM network. We increase the number of ports at WDM nodes so that the volume of traffic to be accommodated in the future can be maximized. To achieve this, we focus on the maximum flow value of each source–destination node–pair. Let $F_{ij}^{(n)}$ denote the maximum flow value of node–pair (i,j) when it is assumed that OXCs on node n are upgraded. Traffic demand to a node–pair, of which the maximum flow value is limited, tends to be blocked because of the lack of the resources. On the other hand, if the volume of the traffic demand is much smaller than the maximum flow value, the demand tends to be accepted. Therefore, we try to increase the maximum flow value of a node–pair in which the ratio of maximum flow value to the expected volume of traffic demand is the lowest. Our scheme for the OXC–deployment problem is described as follows.

Step (1): Select node n that satisfies $\max\limits_{n} \min\limits_{i,j} \dfrac{F_{ij}^{(n)}}{\mu_{ij}^{(x)}}$.

Step (2): Increase the numbers of OXCs ports on node n by δ.

3.C. Routing Algorithm for the Fiber–Deployment Problem

We also try to design a robust WDM network based on the maximum flow value in the fiber–deployment problem. To do this, we propose EMIRA (Enhanced Minimum Interference Routing Algorithm), which is based on MIRA [6], summarized in the Appendix. Since a fixed physical topology is used in MIRA as input information we cannot apply it to our fiber deployment problem where the physical topology is *output* information. EMIRA uses the layered-graph described in [9] instead of the physical topology. The layered-graph has W layers as shown in Figs. 3 and 4, where W is the number of multiplexed wavelengths. In the graph of the wth layer, a vertex (i.e., node) corresponds to an OXC for wavelength w and an edge (expressed as $e_{(index\_of\_link),(index\_of\_wavelength)}$ in Fig. 4) corresponds to a set of wavelength w's available resources between two OXCs. The link cost of wavelength w on link s is given by Eq. (1). If no wavelength w is idle between an OXC-pair, the corresponding link cost is infinity. According to the shortest path routing on the layered-graph, we determine where to route lightpaths that are to accommodate the traffic demand. We lease dark fibers on the basis of where lightpaths are to be set up. As a result, we can design the physical topology that can accommodate traffic demand.

The key idea behind EMIRA is to select a route such that sufficient equipment in addition to wavelength resources remains for potential traffic demand in the future. In EMIRA, we assign a link cost expressed by Eq. (1) to each link on the layered-graph. It takes into account the remaining resources as well as *critical link*s. Critical links are defined as links with properties that whenever traffic demand is routed over them the maximum flow values of one or more source–destination pairs decrease [6]. EMIRA gives priority to determining a path that has abundant remaining resources by utilizing the amount of remaining

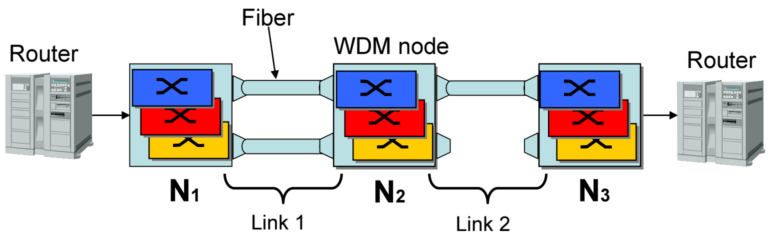

Fig. 3. Original network of the layered graph

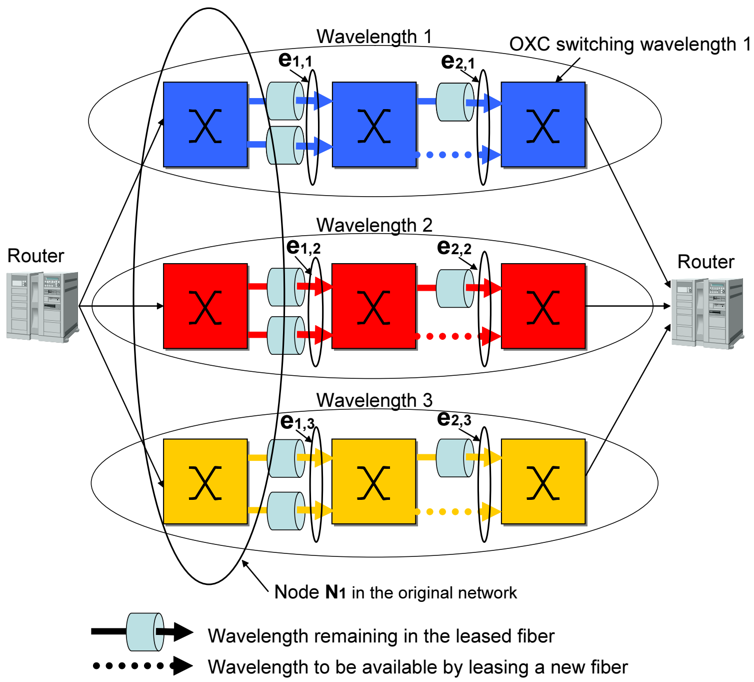

Fig. 4. Example of layered graph: The number of wavelengths is 3

resources as the denominator of link cost.

$$Cost_{sw} = \begin{cases} \infty & \text{if } B_{sw} = 0 \text{ and } C_{sw} = 0, \\ 0 & \text{if } A_{sw} = 0,\ B_{sw} \neq 0 \text{ and } C_{sw} = 0, \\ \dfrac{A_{sw}}{B_{sw} \times \frac{A_{sw}}{Q(Q-1)} + C_{sw}} & \text{otherwise,} \end{cases} \tag{1}$$

where

A_{sw}: Number of node–pairs that regard wavelength w on link s as a *critical link*. How to calculate A_{sw} is explained in the Appendix.

B_{sw}: The least number of remaining OXC ports for wavelength w at two nodes connected to link s.

C_{sw}: Number of idle wavelength w in multiple fibers on link s.

Q: Number of nodes in the physical topology. $Q \times (Q-1)$ is the total number of node–pairs, that is, the upper bound value of A_{sw}.

When $B_{sw} = 0$ and $C_{sw} = 0$, the link cost of wavelength w on link s is infinity because there is no wavelength to set up lightpaths. When $A_{sw} = 0$, $B_{sw} \neq 0$ and $C_{sw} = 0$, the link cost of wavelength w on link s is 0 because wavelengths remain by leasing new fibers and no node–pair regards it as a critical link.

By introducing B_{sw}, we place priority on selecting a route where more OXC ports remain. However, we do not simply use the number of remaining OXC ports as a link cost. Instead, we introduce a weight of B_{sw} that changes according to how congested wavelength w on link s is. This is based on the idea that we should use numerous remaining OXC ports in the congested link while keeping remaining OXC ports for the future traffic demand in links that are not congested. A congested link is defined as one that many node–pairs regard as a critical link. Therefore, we use the ratio of A_{sw} to the upper bound value of A_{sw} as the weight of B_{sw}. C_{sw} assigns a higher priority to selecting wavelengths remaining in leased fibers than to selecting wavelengths that will become available after a new fiber is leased. By doing this, the required number of fibers can be reduced.

The outputs of EMIRA are (1) the route and the wavelength of a lightpath to be set up, (2) the links where we need to lease new dark fibers. The layered–graph in EMIRA consists of wavelengths remaining on leased fibers, and potential wavelengths that will become available when new fibers are leased. Thus, when EMIRA finds the route for a lightpath, we can always set up the lightpath.

EMIRA is described as follows.

INPUT

- Layered-graph that consists of existing OXCs, remaining wavelengths and potential wavelengths that will become available when new fibers are leased.
- Traffic demand from node i to node j.

OUTPUT

- The route of a lightpath and its wavelength between nodes i and j.
- The links where we need to lease dark fibers between nodes i and j.

ALGORITHM

Step (1): Calculate the A_{sw} by following these steps.

Step (1-a): Calculate the maximum flow of each source–destination pair except (i, j) by using the Fold–Fulkerson algorithm [10] and obtain critical links for each source–destination pair.

Step (1-b): Calculate A_{sw} from Eq. (2), which is described in Appendix.

Step (2): Calculate B_{sw} and C_{sw} on the layered–graph.

Step (3): Calculate the link cost on each link by applying A_{sw}, B_{sw} and C_{sw} to Eq. (1).

Step (4): Select a path using Dijkstra's shortest path algorithm.

Step (5): Set a lightpath on the route obtained in Step (4). If no wavelength is available, lease a new fiber and connect it to the OXCs.

4. Numerical Evaluation and Discussions

In this section, we evaluate our scheme in single period network design scenario. First, we describe a simulation model in Section 4.A. We then show numerical results and discussion in Section 4.B.

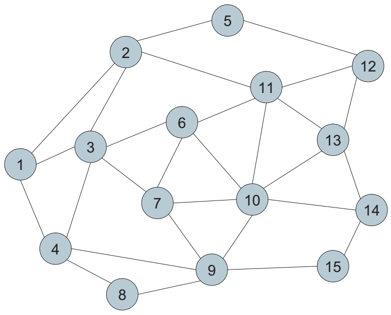

Fig. 5. Network model

4.A. Simulation Condition

We use the 15–node network model in Fig. 5. There are initially no fiber on each link and when we need them, we lease dark–fibers. We assume that the traffic demand is normalized into the wavelength capacity; that is, traffic demand is equivalent to the number of lightpaths that have been requested to be set up. The number of wavelengths multiplexed on a fiber, W, is set to 4. In our proposed algorithm, the number of OXC ports is initially set to 8 ($p = 8$), and increases by 2 ports ($\delta = 2$). We compare the network designed with our scheme with the one designed to minimize the OXC cost, which is designed by the heuristic optimization method [11]. This belongs to the class of "deterministic heuristics". In this class of methods, an initial topology, which accommodates the traffic demand, is designed by adopting a set of heuristic criteria (e.g., MIN-HOP (Minimum Hop routing) and LLR (Least Loaded Routing)). Then, the network is globally optimized by trying to reroute the traffic demand. The heuristic optimization method has proved to be a superior algorithm which obtains sub–optimal results with less computational effort than ILP (Integer Linear Programming). We use MIN-HOP in the heuristic optimization method. We call these two networks as follows.

PT_{ADD} : Network designed with our proposed scheme to be robust against the traffic changes.

PT_{hom} : Network designed with the heuristic optimization method [11] to minimize OXC costs.

When the traffic demand actually occurs, we must determine which route will accommodate it. Since actual traffic demand occurs dynamically, the route that is assumed to accommodate it during the design stage can differ from the route that actually accommodates it. As a routing algorithm, we use MIRA [6] for both PT_{ADD} and PT_{hom} because it can accommodate as much unpredicted traffic as possible.

4.B. Evaluation Results

We evaluate the performance of PT_{ADD} and PT_{hom} when the traffic change occurs, that is, the value of σ in actual traffic demand changes. We express the predicted traffic as a traffic matrix, $\boldsymbol{T}_0 = \{\mu_{ij}\}$. μ_{ij} is the traffic volume requested by node–pair (i, j). We calculate the cost of $v \times v$ OXC as $\frac{v^2}{64} \times C_8$ (C_8 is the cost of a 8×8 OXC), assuming that the non–blocking OXCs are implemented as crossbar switches. In the PT_{hom}, the OXC cost is calculated based only on the number of ports actually used.

We now discuss the evaluation results when the traffic change occurs. The original heuristic optimization method does not incorporate cases where traffic demand that actually

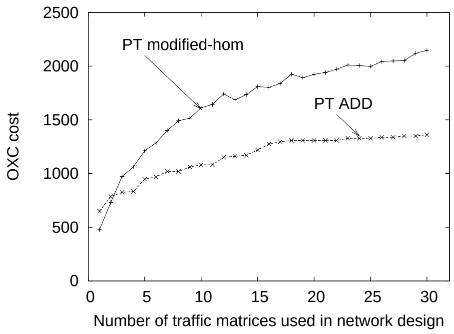

Fig. 6. OXC costs of PT_{ADD} and $PT_{\mathrm{modified-hom}}$ (traffic $\mu = 2, \sigma = 1$)

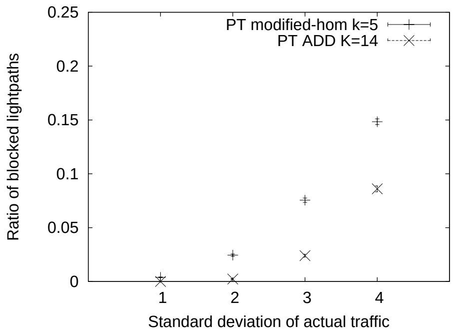

Fig. 7. Ratios of blocked lightpaths in PT_{ADD} and $PT_{\mathrm{modified-hom}}$

occurs varies, that is, it always regards σ as 0. We modify the original heuristic optimization method to accommodate traffic changes. When K different traffic matrices are inputted, the modified heuristic optimization method first generates a traffic matrix, $\boldsymbol{T}_{\max}$. Each element $t_{ij}^{\max}$ of $\boldsymbol{T}_{\max}$ equals the maximum traffic volume of node–pair (i, j) out of K traffic matrices ($t_{ij}^{max} = \max_k(t_{ij}^k), (k = 0, 1, 2, \ldots, K-1)$). The modified heuristic optimization method, then, can be used to design a network that accommodates $\boldsymbol{T}_{\max}$ with minimum OXC cost. We call the network designed with the modified heuristic optimization method $PT_{\mathrm{modified-hom}}$. Figure 6 shows the OXC costs of PT_{ADD} and $PT_{\mathrm{modified-hom}}$ when we use $\mu = 2$ and $\sigma = 1$. The OXC costs represent the relative values to the cost of an 8×8 OXC. The horizontal axis is the number of traffic matrices that are used by each design method. The OXC cost value at the kth index of the horizontal axis shows traffic matrices (from $\boldsymbol{T}_0$ to $\boldsymbol{T}_{k-1}$). t_{ij}^k (i.e., each element of $\boldsymbol{T}_k$) is a value of the random variable that follows a normal distribution, $N(\mu, (\sigma)^2)$. The cost of $PT_{\mathrm{modified-hom}}$ does not keep increasing although $\boldsymbol{T}_{\max}$ keeps rising as the number of inputted traffic matrices increases. This is because the estimation–error between the optimal OXC cost and the sub–optimal OXC cost obtained by the modified heuristic optimization method can change as the inputted traffic matrices changes. Note that the cost of $PT_{\mathrm{modified-hom}}$ exceeds that of PT_{ADD} as the number of traffic matrices used in network design gets larger. We can say that it is pointless trying to accommodate the maximum traffic volume of predicted traffic matrices, $\boldsymbol{T}_{\max}$.

To evaluate how cost–effectively our method permits the network equipment to be used, we compare PT_{ADD} with $PT_{\mathrm{modified-hom}}$, both of which are designed with almost the same OXC cost. For this purpose, we selected PT_{ADD} designed with $K = 14$, $\mu = 2$, and $\sigma = 1$ and $PT_{\mathrm{modified-hom}}$ designed with $K = 5$, $\mu = 2$, and $\sigma = 1$. The former

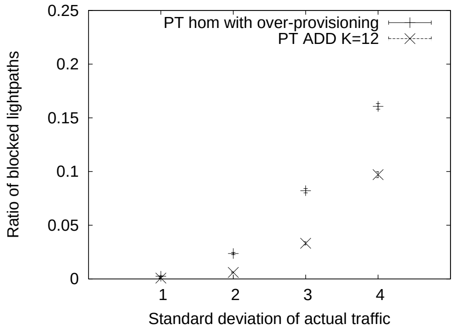

Fig. 8. Ratios of blocked lightpaths in PT_{ADD} and PT_{hom} with over-provisioning

costs 1169 and the latter 1211. These costs represents the OXC cost. The numbers of fibers needed by PT_{ADD} and $PT_{\mathrm{modified-hom}}$ are also almost the same; PT_{ADD} needs 381 fibers and $PT_{\mathrm{modified-hom}}$ does 422 fibers. Figure 7 shows the average ratio of blocked lightpaths with a 95% confidence interval in PT_{ADD} and $PT_{\mathrm{modified-hom}}$ when the traffic change of the actual traffic (σ) varies from 1 to 4. The horizontal axis is the value of σ in the actual traffic. When the traffic change is the same as predicted ($\sigma = 1$), PT_{ADD} shows about 0.00002 and does $PT_{\mathrm{modified-hom}}$ about 0.0038. Both networks can accommodate almost all the requested lightpaths when the traffic change is the same as predicted. When the traffic change is larger than predicted, the difference in the ratio of blocked lightpaths between PT_{ADD} and $PT_{\mathrm{modified-hom}}$ gets larger (0.022, 0.051 and 0.064 when σ is 2, 3 and 4, respectively).

We finally compare our design method with the over–provisioning approach. Over–provisioning is a simple way of designing a network, which can accommodate more traffic demand than that predicted. Now let us assume a situation where the the traffic change (σ) is predicted as 1 in designing the network. Here, our method can be used to design a network with traffic matrices that follow $N(2, 1^2)$ while the heuristic optimization method for over–provisioning can be used to design a network that can accommodate more traffic volume than 2 in each node–pair. Figure 8 shows the ratio of blocked lightpaths with a 95% confidence interval in PT_{ADD} with $K = 12$, $\mu = 2$, and $\sigma = 1$ and PT_{hom} with $K = 1$, $\mu = 3$, and $\sigma = 0$. In this case, the cost of $PT_{\mathrm{ADD}}$is almost same as that of PT_{hom} with over–provisioning, which tries to accommodate 1.5 times as much traffic demand as predicted. The former costs 1151 and the latter 1156. PT_{ADD} needs 365 fibers and PT_{hom} does 462 fibers. We assume that the traffic change of the actual traffic would vary from 1 to 4 in Fig. 8. The horizontal axis shows the value of the traffic change. PT_{ADD} has a lower ratio of blocked lightpaths than PT_{hom} over all σs. Similarly the difference in the ratio of blocked lightpaths between PT_{ADD} and PT_{hom} gets larger (0.0016, 0.018, 0.049 and 0.063 when σ is 1, 2, 3 and 4, respectively). Our method can design the cost–effective network by properly adjusting the number of OXC ports.

5. Conclusion

In this paper, we have proposed a novel design method of WDM network that is robust against traffic changes. Through the simulation, we evaluated how cost–effectively we use the network equipment by comparing the network that our proposed method designs with those that the conventional methods design, both of which need almost the same OXC cost. As a result, we have shown the network that our proposed method designs achieves lower ratio of blocked lightpaths than the one obtained by the over–provisioning approach

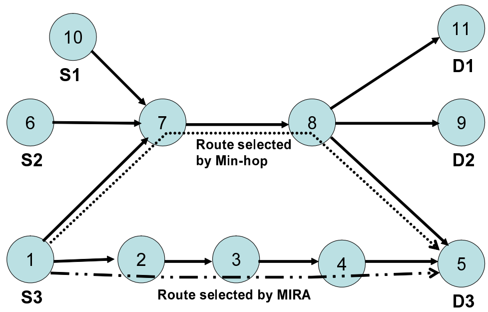

Fig. 9. Routes selected by MIN-HOP and MIRA

does. We conclude that our proposed method designs a robust WDM network in the cost–effective way.

Several topics are still left for future work. One of them is designing a robust WDM network where not only working paths but also backup paths are set up. In such a network, backup paths can be used for accommodating the unpredicted request of lightpaths. We will consider a method to set up backup lightpaths that can accommodate the traffic changes as well as correspond to the failure of working paths.

Appendix: MIRA (Minimum Interference Routing Algorithm)

Here we briefly explain MIRA [6]. MIRA dynamically determines the routes needed to meet traffic demand one–by–one as they occur, without a priori knowledge of future traffic demand. The key idea behind MIRA is to select a path that minimizes interference with potential future traffic demands between other source–destination pairs. Figure 9 illustrates how MIRA selects a route. There are three source–destination pairs, (S1,D1), (S2,D2), and (S3,D3) in the network. When (S3,D3) requires one lightpath, the existing MIN-HOP (minimum hop–count) routing algorithm selects a route $1 \rightarrow 7 \rightarrow 8 \rightarrow 5$. MIN-HOP is a routing algorithm that selects a route with minimum–hop counts. However, the link from node 7 to node 8 is also used for both (S1,D1) and (S2,D2). Setting up a lightpath on route $1 \rightarrow 7 \rightarrow 8 \rightarrow 5$ affects the potential use for (S1,D1), (S2,D2). MIRA avoids passing on a route that has the potential for a lot of traffic. It selects route $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5$, which minimizes the interruption to other node–pairs.

To move on from the concept of minimum interference links to a viable routing algorithm that uses maximum flow and shortest path algorithms, MIRA incorporates the notion of "critical links". The "critical links" are defined as links with the property that whenever traffic demand is routed over them the maximum flow values of one or more source–destination pairs decrease. MIRA counts the number of node–pairs for each link, which regard the link as a "critical link", and sets it to the link cost to cope with future traffic demand. MIRA assigns the link cost, $Cost_{sw}$, to wavelength w on link s and determines the route using Dijkstra's shortest path algorithm. $Cost_{sw}$ is represented by A_{sw}, which is the number of source–destination pairs whose critical links include wavelength w on link s. That is,

$$Cost_{sw} \quad = \quad A_{sw} = \sum_{i,j} x_{ij}^{sw} a_{ij}^{sw}, \tag{2}$$

where

x_{ij}^{sw}: If the maximum flow from node i to node j includes wavelength w on link s, then $x_{ij}^{sw} = 1$. Otherwise $x_{ij}^{sw} = 0$.

a_{ij}^{sw}: If wavelength w on link s is available after maximum flow has been carried from node i to node j, then $a_{ij}^{sw} = 0$. Otherwise $a_{ij}^{sw} = 1$.

Acknowledgments

This work was supported in part by "The 21st Century Center of Excellence Program" and a Grant-in-Aid for Scientific Research (A) 14208027 from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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