PLANNING METHOD OF ROBUST WDM NETWORKS AGAINST TRAFFIC CHANGES

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Abstract

Many researches have been investigated on planning and/or designing WDM networks, but most of them assume that the future traffic demand is known beforehand. However, it is difficult to predict the future traffic demand accurately in a practical sense since there are various types of data traffic with different traffic characteristics. More flexible planning/design methods are necessary to accommodate the unpredicted traffic demand. 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. We resolve such a problem by incrementally installing OXCs and fibers until they reach a condition that a robust WDM network needs to fulfill. Our approach for designing such a network is divided into two problems; the *OXC–deployment problem* and the *fiber–deployment problem*. In both problems, 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. We compare our developed scheme with the existing methods using various traffic matrices. The results 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.

The above–mentioned method is intended to be applied for installing the network at the beginning, that is, a single–period design. Since the cost of optical components is expected to decrease due to the technological advance, it is better to upgrade the network at regular intervals to deploy most recent optical components; namely, the most economical ones than to upgrade the network at once. Our method is then extended to a multi–period network design method, where network equipments are deployed during each period (e.g., quarter or year), which is part of long–term planning. We repeatedly use the above–mentioned method period–by–period. In designing over multiple periods, our scheme can design a robust and cost–effective WDM network by taking advantage of the cost reduction of the optical components due to the technological advance.

Keywords: Robust WDM Network, Traffic Changes, Multi-Period Network Design, ADD Algorithm, OXC Deployment

1. Introduction

Wavelength division multiplexing (WDM) technology that multiple wavelengths carry different optical signals on a single optical fiber is expected 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 WDM networks have been proposed [1]. We might use these methods to solve the routing and wavelength assignment for lightpaths over a physical network that is the actual network where the OXCs and fibers are connected to each other. Planning to minimize the cost of the physical network in a single period, of which all equipments are installed at the beginning has also been studied [2–4]. Planning in a single period is to design the network that can accommodate traffic demand occurring during the period. However, 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 [5]), in practice, it is difficult to predict traffic pattern of each source–destination pair, because there are various types of data traffic such as video streams and voice traffic with different traffic characteristics. More significantly, the advent of popular World Wide Web servers or data centers has drastically affected traffic demand. We may have several traffic patterns during the period. Traffic of a small fraction of source–destination pairs may be increased rapidly in the period.

In order to cope with the unpredictable traffic demand, we try to design a network accommodating several predicted traffic patterns that follow a certain distribution (e.g., normal or exponential distribution). 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.

In this paper, we propose a scheme for designing robust WDM networks in a single period without a prior knowledge of traffic patterns that will occur during the design period. Our objective is to design a WDM network that will accommodate a variety of traffic patterns, that is, to design a network that is robust against traffic changes. One way to meet this objective is to design a network that accommodates as much future traffic as possible. To achieve this, we incrementally extend the size of OXCs and lease a number of 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 (ADDA) to which we modify the traditional ADD algorithm [6]. By allocating the OXCs and the fibers in the ADD algorithm appropriately, we can establish a robust WDM network subject to the traffic uncertainties. Also, the network has a cost-effective feature.

Extending the size of OXCs, which we call *OXC–deployment problem*, involves determining that how large OXCs are necessary 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 *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) [7] and MOCA (Maximum Open Capacity Routing Algorithm) [8]. 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 propose a routing and fiber/wavelength assignment algorithm that we call EMIRA (Enhanced Minimum Interference Routing Algorithm).

Our scheme is also useful for period–by–period network planning for a long–term such as several years. There are two kinds of long–term planning approaches, a single period planning and a multi-period one. The former regards the long–term as one design period and initially installs all the equipments needed during the long–term while the latter incrementally installs the equipments period–by–period (e.g., quarter–by–quarter or year–by–year). We can expect that it is more cost–effective to deploy as few optical components as possible during each period by applying a multi–period planning approach since progress in technology will reduce the overall cost of WDM network resources with the passage of time [9–10]. In the multi-period network design, we repeatedly apply our design method for a single period over the multiple periods. Our multi–period scheme can design a robust and cost–effective network when the cost of optical components decreases at some discount rate.

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 and 5, we show the numerical results obtained through simulations and evaluate the proposed scheme in the single period and multi-period network design scenarios, respectively. In Section 6, we present our conclusions and directions for a future work. The explanation of MIRA, a routing algorithm that our EMIRA is based on is given in Appendix.

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

2.1 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. Wavelength conversion is not allowed at WDM nodes. As illustrated in Fig. 1, the number of optical fibers between two WDM nodes may not be identical.

We intend our network design method for WDM lightpath networks, where each traffic demand is accommodated on the 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*.

2.2 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 at links to design a robust WDM

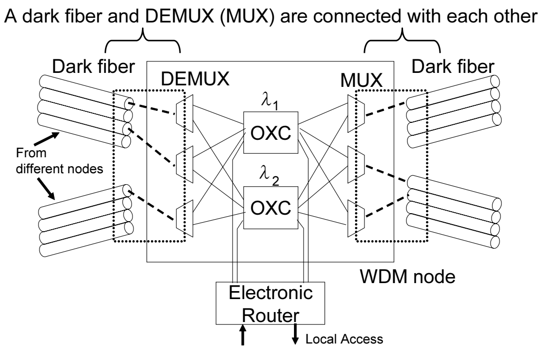

Figure 1. WDM node architecture

network. The dark fibers are connected to available DEMUXs/MUXs as long as there are available ports at the OXC. On the other hand, we obtain 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 during a single design period. 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.

- In the multi-period network design, we do not reconfigure the node equipments deployed during the previous periods (i.e., We do not reconnect any fibers that have previously been connected to MUXs/DEMUXs or do not replace OXCs already installed) because this would interrupt services that are then running.

2.3 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 $X\%$ rather 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}.

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.

3. WDM Network Design Method Robust against Traffic Changes

3.1 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 ADD algorithm (See Fig. 2).

(1) OXC–deployment problem: Given the expected traffic demand and a WDM physical topology, we determine how large OXCs are newly necessary to design a robust network. To achieve this, we first find the

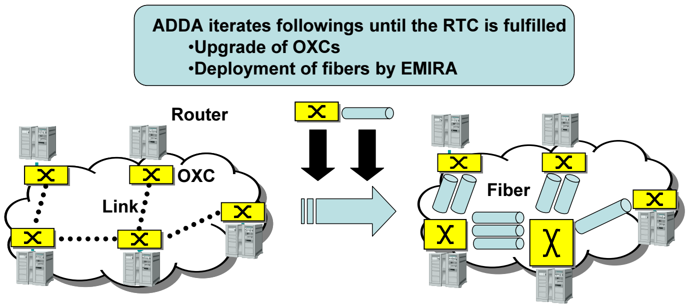

Figure 2. Outline of WDM network design

node-pair that limits the traffic volume accommodated by the network. We then determine the OXC port 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 [6]. 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 different points from the traditional one. The first is the condition to end the iteration. We stop iteration when we achieve robust feature which is indicated by RTC in our ADD algorithm. 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.

<u>INPUT</u>

$\boldsymbol{G}_{(x-1)}$: 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, $\mu_{ij}^{(x-1)}$.

$\mathbf{\Sigma}^{(x)}$: 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 on nodes. We call 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 ADDA. 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 3.2, 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 3.3). 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 [5]. 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), all the OXCs on the same node are simultaneously upgraded so that the number of ports of them are kept same as that of the OXC. We regard the designed WDM network that accommodates all the traffic patterns generated in Step (1) as a robust one.

3.2 Scheme for the OXC–Deployment Problem

The objective of the OXC–deployment problem is to determine that how large OXCs are necessary 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 $\max_{n} \min_{i,j} \frac{F_{ij}^{(n)}}{\mu_{ij}^{(x)}}$.

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

3.3 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 [7], 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 [11] 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 jth layer, a vertex (i.e., node) corresponds to an OXC for wavelength j and an edge (expressed as $e_{(index\_of\_link),(index\_of\_wavelength)}$ in Fig. 4) corresponds to a set of wavelength j's available resources between two OXCs. Each link cost is given by Eq. (1). If no wavelength j 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 [7]. EMIRA gives priority to determining a path that has abundant remaining resources by utilizing the amount of remaining resources as the denominator of link cost.

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

where

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

B_{ij}: The least number of remaining OXC ports for wavelength j at two nodes connected to link i.

C_{ij}: Number of idle wavelength j in multiple fibers on link i.

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_{ij}.

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

By introducing B_{ij}, we place priority on selecting a route where more OXC ports remain. However, we do not simply use the number of remaining OXC

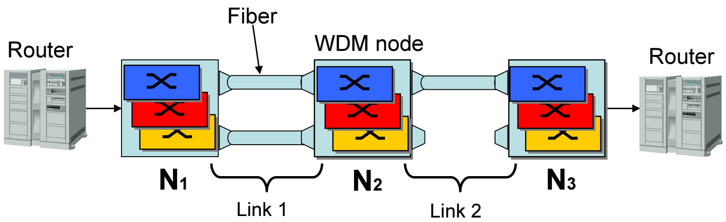

Figure 3. Original network of the layered graph

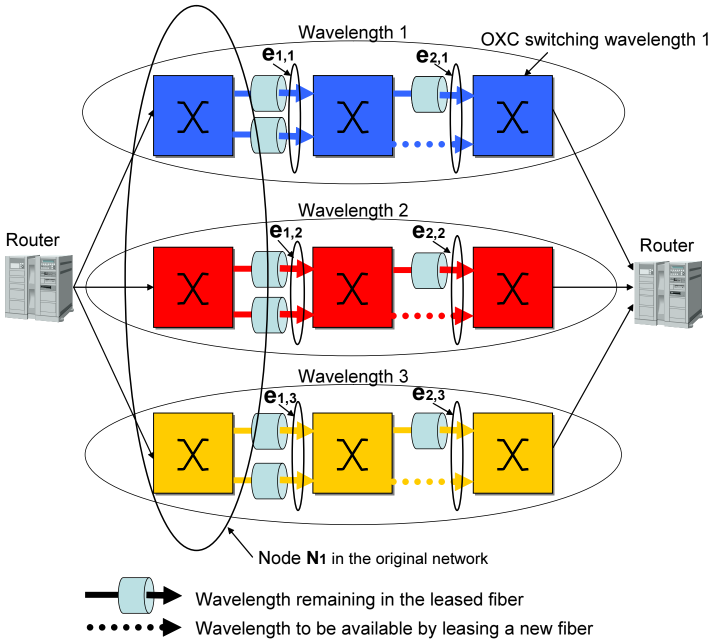

Figure 4. Example of layered graph: The number of wavelengths is 3

ports as a link cost. Instead, we introduce a weight of B_{ij} that changes according to how congested wavelength j on link i 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_{ij} to the upper bound value of A_{ij} as the weight of B_{ij}. C_{ij} 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 s to node t.

OUTPUT

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

ALGORITHM

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

Step (1-a): Calculate the maximum flow of each source–destination pair except (s, t) by using the Fold–Fulkerson algorithm [12]and obtain critical links for each source–destination pair.

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

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

Step (3): Calculate the link cost on each link by applying A_{ij}, B_{ij} and C_{ij} 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

4.1 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 [13]. This belongs to the class of "deterministic heuristics". In this class of methods, an initial topology, which

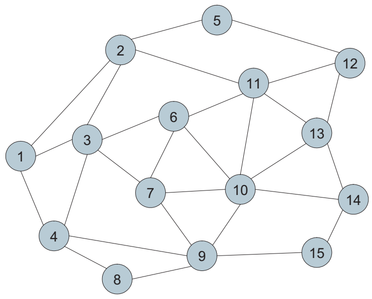

Figure 5. Network model

accommodates the traffic demand, is designed by adopting a set of heuristic criteria (e.g., MIN-HOP (Minimum Hop routing) and LLR (Leased 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.

$PT_{\rm ADD}$: Network designed with our proposed scheme to be robustness against the traffic changes.

$PT_{\rm hom}$: Network designed with the heuristic optimization method [13] 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 [7] for both $PT_{\rm ADD}$ and $PT_{\rm hom}$ because it can accommodate as much unpredicted traffic as possible.

4.2 Evaluation Results

We first evaluate the performance of $PT_{\rm ADD}$ and $PT_{\rm hom}$ when predicted traffic demand actually occurs. 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 $\frac{v^2}{4} \times C_2$ (C_2 is the cost of a 2×2 OXC), assuming that the non–blocking OXCs are implemented as crossbar switches. In the $PT_{\rm hom}$, the OXC cost is calculated based only on the number of ports actually used.

We now discuss the evaluation results when actual traffic demand follows a predicted distribution. Here, predicted distribution means the μ and σ of traffic demand actually occurring are the same as the μ and σ of traffic demand used to design the network. The original heuristic optimization method does not incorporate cases where traffic demand that actually 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

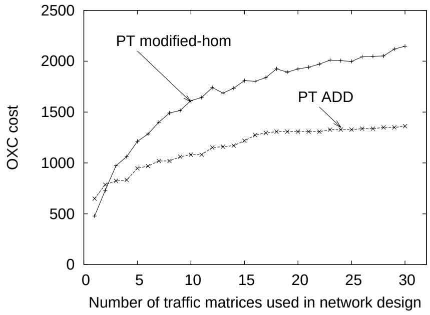

Figure 6. OXC costs of $PT_{\rm ADD}$ and $PT_{\rm modified-hom}$ (traffic $\mu = 2, \sigma = 1$)

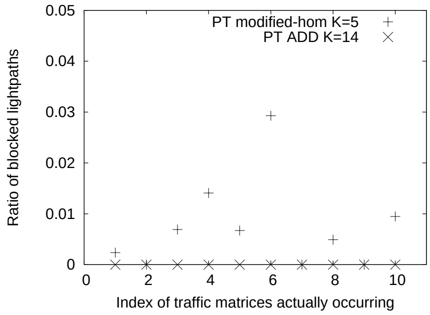

Figure 7. Ratios of blocked lightpaths in $PT_{\rm ADD}$ and $PT_{\rm modified-hom}$ (traffic $\mu = 2, \sigma = 1$)

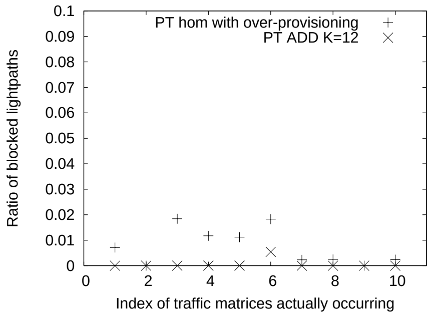

Figure 8. Ratios of blocked lightpaths in $PT_{\rm ADD}$ and $PT_{\rm hom}$ with over-provisioning (traffic $\mu = 2, \sigma = 1$)

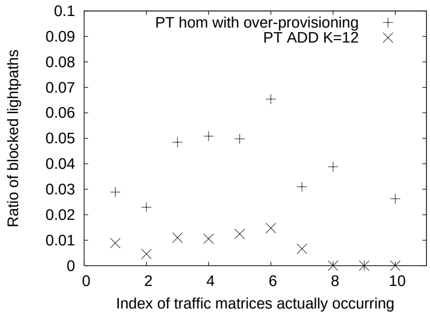

Figure 9. Ratio of blocked lightpaths in $PT_{\rm ADD}$ and $PT_{\rm hom}$ with over-provisioning (traffic $\mu = 2, \sigma = 2$)

modified heuristic optimization method first generates a traffic matrix, $\boldsymbol{T}_{\rm max}$. Each element $t_{ij}^{\rm max}$ of $\boldsymbol{T}_{\rm max}$ 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 $\boldsymbol{T}_{\rm max}$ with minimum OXC cost. We call the network designed with the modified heuristic optimization method $PT_{\rm modified-hom}$. Figure 6 shows the OXC costs of $PT_{\rm ADD}$ and $PT_{\rm modified-hom}$ 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 $PT_{\rm modified-hom}$ does not keep increasing although $\boldsymbol{T}_{\rm max}$ 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 $PT_{\rm modified-hom}$ exceeds that of $PT_{\rm ADD}$ 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 $PT_{\text{modified-hom}}$, 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 $PT_{\text{modified-hom}}$ designed with $K = 5$, $\mu = 2$, and $\sigma = 1$. The former costs 1169 and the latter 1211. These costs represents the OXC cost. The numbers of fibers needed by PT_{ADD} and $PT_{\text{modified-hom}}$ are also almost the same; PT_{ADD} needs 381 fibers and $PT_{\text{modified-hom}}$ does 422 fibers. Figure 7 shows the ratio of blocked lightpaths in PT_{ADD} and in $PT_{\text{modified-hom}}$ when the actual traffic follows a $N(2, 1^2)$ normal distribution. The horizontal axis is the index of the traffic matrix that actually occurs. In each occurrence of traffic demand, PT_{ADD} can set up all the requested lightpaths while $PT_{\text{modified-hom}}$ shows the ratio of blocked lightpaths between 0 and 0.03.

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 occurrence of traffic demand is predicted to follow $N(2, 1^2)$. 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 of 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 $PT_{\text{ADD}}$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 traffic demand actually occurring would follow $N(2, 1^2)$ in Fig. 8. The horizontal axis shows the index of traffic matrix that actually occurs. PT_{ADD} has a lower ratio of blocked lightpaths than PT_{hom}. In a situation where there is much change in traffic actually occurring ($\sigma = 2$), the difference in the ratio of blocked lightpaths between PT_{ADD} and PT_{hom} gets larger as shown in Fig. 9. Our method can design the cost–effective network by properly adjusting the number of OXC ports.

5. Multi-Period Network Design

5.1 Approaches to Long–Term Network Design

We next focus on the *multi-period network design* scenario. In [10], two approaches to a five-year network design are proposed. The first is the algorithm O5, which is used to design a network by regarding five years as a single period. The other is O1+, which is used to design a network period–by–period. O1+ determines the route for traffic demand during each period without knowledge about the future traffic. The optical components are deployed based on the current traffic demand and optical components that were already deployed in the previous periods. Accordingly, the optimal deployment, where optical components are deployed from nothing, is not achieved. However, the O1+ has an advantage in that it can be used to deploy up–to–date optical components. These can be purchased at less cost than during the previous periods due to reduced optical component costs caused by the technological advances. In a multi-period network design, we repeatedly apply our scheme period-by-period just as we do O1+. The difference is that the objective of ours is to design a network robust against traffic changes while that of O1+ is to minimize the cost.

5.2 Simulation Condition

We again use the 15–node network model shown in Fig. 5. Initially, there is no fiber on any link and when we need them, we lease dark–fibers on a link. We set W, p, and δ to 4, 2, and 2 respectively. To insure continuity of services, we do not replace the optical components already installed. We only reroute lightpaths set up in the previous periods, which needs much less time than that required to replace the optical components. To take into account the reduction of cost of the optical components by the technical advance, we introduce the *discount rate*, which determines how much the cost of OXC decreases per design period.

We compare the network designed with our scheme to the one designed with O5. The comparison of our scheme with O1+ is not performed here since the network design in each period is same as the single period network design. In the five–period network design, our scheme deploys five non–blocking OXCs for a wavelength on each node (a non–blocking OXC is deployed during each period following the restrictions described in Section 2.2). As a result, a cluster consisting of the five OXCs forms a blocking switch for a wavelength on each node. This cluster includes more available OXC ports than a non–blocking OXC switch does with the same OXC cost. In the evaluation of the ratio of blocked lightpaths, we take into account this effect on the ratio of blocked lightpaths.

We use the heuristic optimization method [13] in O5 to design a network for minimizing the OXC cost. We call the network designed with O5 as follows.

$PT_{(\mathrm{hom,O5})}$: Network designed with the heuristic optimization method in the way of O5 to minimize OXC costs .

Traffic demand occurs uniformly at each node–pair. We assume that node-pairs where traffic demand occurs request one lightpath ($\mu_{ij}^{(1)} = 1$) during the first period. Each volume of traffic is assumed to double period-by-period. During the last period ($x = 5$), the volume of traffic equals 16 ($\mu_{ij}^{(5)} = 16$). We also assume that $\sigma_{ij}^{(1)} = 1$ and it would double in each period because the traffic changes become larger as traffic volume grows.

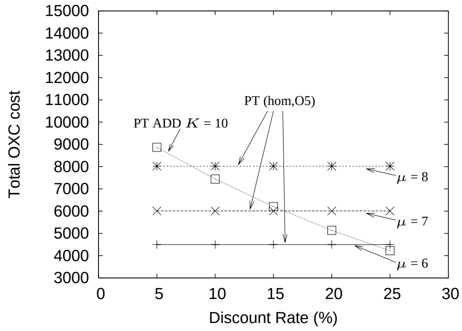

Figure 10. Comparison of the OXC cost of PT_{ADD} with that of $PT_{(\mathrm{hom,O5})}$

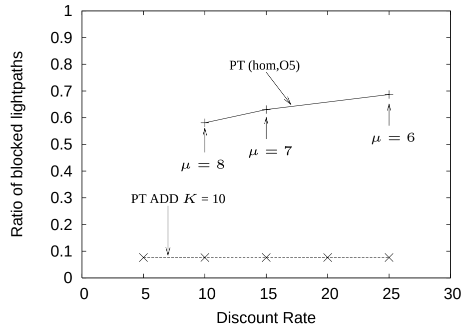

Figure 11. Average ratio of blocked lightpaths in PT_{ADD} and $PT_{(\mathrm{hom,O5})}$

5.3 Evaluation Results

We first compare the total OXC cost over five periods. Figure 10 shows the total OXC cost needed to design PT_{ADD} and $PT_{(\mathrm{hom,O5})}$s. As to $PT_{(\mathrm{hom,O5})}$, three kinds of $PT_{(\mathrm{hom,O5})}$s with different μ values ($\mu = 6, 7$, and 8) are shown. These $PT_{(\mathrm{hom,O5})}$s are designed so that their OXC costs are almost the same as that of PT_{ADD} in the corresponding *discount rate*. For example, the costs of $PT_{(\mathrm{hom,O5})}$ with $\mu = 6, 7$, and 8 are almost the same as that of PT_{ADD} when discount rate is 25%, 15%, and 10%, respectively. To evaluate how cost–effectively our scheme designs the network, we compare the ratio of blocked lightpaths over five periods in PT_{ADD} and $PT_{(\mathrm{hom,O5})}$, both of which are designed with almost the same OXC cost.

We next compare the ratio of blocked lightpaths. Figure 11 shows the average ratio of blocked lightpaths over five design periods in PT_{ADD} and $PT_{(\mathrm{hom,O5})}$ when all the patterns in three traffic matrices are generated, which follow the predicted normal distribution. In three discount rates $10\%, 15\%$, and 25%, appropriate $PT_{(\mathrm{hom,O5})}$, whose cost is almost the same as that of PT_{ADD} at the discount rate, is selected. For discount rates 5% and 20%, appropriate $PT_{(\mathrm{hom,O5})}$ cannot be obtained because there exists no $PT_{(\mathrm{hom,O5})}$ whose OXC cost is almost the same as that of PT_{ADD}. For all the discount rates, PT_{ADD} can accommodate much more lightpaths than $PT_{(\mathrm{hom,O5})}$ does. This is because PT_{ADD} can utilize much more OXC ports than $PT_{(\mathrm{hom,O5})}$ does by deploying a cluster consisting of the five OXCs instead of an non–blocking OXC that costs higher than the blocking one with the same number of OXC ports. If $PT_{(\mathrm{hom,O5})}$ also deploys a blocking switch that consists of some non–blocking OXCs instead of a non–blocking switch, $PT_{\mathrm{hom,O5}}$ will show better performance. The comparison of such a $PT_{\mathrm{hom,O5}}$ with PT_{ADD} is our future work.

6. 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 does. We have also shown that our scheme designs a cost–effective and robust network in the long–term network planning scenario. In the long–term planning situation, our scheme repeatedly upgrades the network period–by–period, which leads to taking advantage of the cost reduction of the optical components. The network designed with our scheme can accommodate more lightpaths than that designed with O5 over five design period regardless of the value of the discount rate. 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.

Acknowledgments

This work was supported in part by “The 21st Century Center of Excellence Program”, the Telecommunications Advancement Organization of Japan (TAO), and the Ministry of Education, Science and Culture, Grant-in-Aid for (A)(1), 14208027, 2002.

Appendix: MIRA (Minimum Interference Routing Algorithm)

Here we briefly explain MIRA [7]. 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 12 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

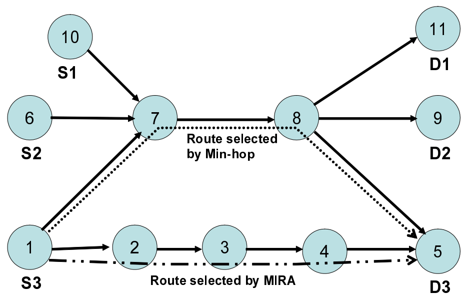

Figure 12. Routes selected by MIN-HOP and MIRA

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, $Cost_{ij}$, to wavelength j on link i and determines the route using Dijkstra's shortest path algorithm. $Cost_{ij}$ is represented by A_{ij}, which is the number of source–destination pairs whose critical links include wavelength j on link i. That is,

$$Cost_{ij} \quad = \quad A_{ij} = \sum_{s,d} x_{sd}^{ij} a_{sd}^{ij}, \qquad (2)$$

where

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

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

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