Master's Thesis

Title

Planning and Design Methods for Robust WDM Networks subject to Traffic Changes

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Abstract

Many researches have been investigated on planning or designing WDM networks assuming that the future traffic is known beforehand. Practically, it is difficult to predict the future traffic demand accurately since there are various types of data traffic with different traffic characteristics. In this thesis, we propose a scheme to design a WDM network that will accommodate as much traffic as possible against a variety of traffic patterns, that is, robust WDM network. Our straightforward way to meet this objective is to design a network to maximize the volume of future traffic flow. To achieve this simply, we divide the WDM network design problem into two subproblems, the *OXC–deployment problem* and the *fiber–deployment problem*. In both problems, we propose schemes to maximize the volume of traffic demand that can be accommodated in the future by taking into account the maximum flow value of each node–pair. We handle those problems by incrementally extending network resources based on the ADD algorithm. By deploying network resources until they reach a condition that a robust WDM network needs to fulfill, we can design a robust WDM network. We compare our proposed scheme with the existing method using various traffic matrices. The results show that the WDM network designed by our method accommodates all the traffic demand, while the one, designed by the exisiting method with the same cost, cannot accommodate 20% of the traffic demand.

Keywords

WDM (Wavelength Division Multiplexing)

Robust WDM Network

Traffic Changes

ADD Algorithm

OXC Deployment

Fiber Deployment

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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 to accommodate traffic demand [1]. We might use these methods to solve the routing and wavelength assignment for lightpaths over a physical network, which means the actual network where the OXCs and the fibers are connected to each other. Planning or multi-period planning to minimize the cost of the actual network has also been studied [2, 3, 4, 5, 6]. In designing a WDM network over an extended period of time, we can expect that it is more cost–effective to deploy as few optical components as possible during each installation since progress in technology will reduce the overall cost of WDM network resources with the passage of time.

However, in those studies, they design the WDM networks based on an explicit knowledge of future traffic demand and assume that traffic demand between each source–destination pair would multiply in volume by some predetermined amount during each period. While we may be able to estimate total traffic demand in the near future (e.g., Internet traffic doubles each year [7]), in practice, it is difficult to predict traffic patterns, 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.

In this thesis, we propose a scheme for designing robust WDM networks without a prior knowledge of traffic patterns. 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. We also keep in mind that it is cost-effective. One straightforward way to meet this objective is to design a network that accommodates as much future traffic as possible. To achieve this, we divide a design problem into two subproblems; an *OXC–deployment problem* and a *fiber–deployent problem* and we treat these subproblems repeatedly in a single period. More specifically, 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) in which we modify the traditional ADD algorithm in Ref. [8]. By allocating the OXCs and the fibers in these subproblems appropriately, we design a robust WDM network. Also, the network has a cost-effective feature.

The OXC–deployment problem involves determining that how large OXCs are necessary to design a robust WDM network. To achieve this cost–effectively, we upgrade appropriate OXCs based on the ADDA. In this subproblem, we first identify the node with bottleneck, which is determined by obtaining the maximum flow value of each node–pair. The maximum flow value of a source–destination pair means an upper bound for the total amount of available bandwidth in the pair. We then add the given number of input/output ports to OXCs on that node. The network in which the bottleneck is alleviated accommodates larger volume of future traffic flow than networks in which other OXCs are extended.

We also try to design a robust WDM network based on the maximum flow value in the fiber–deployment problem. We determine where to set up lightpaths and where to lease optical fibers. There are various routing algorithms that can accomplish maximum flow value problem. 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) [9] and MOCA (Maximum Open Capacity Routing Algorithm) [10]. 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). EMIRA determines where to deploy optical fibers as well as assigning the routes, fibers and wavelengths of lightpaths. It first creates a layered–graph based on the nodal equipments, dark fibers, both of which are already installed. It then calculates the shortest path for each traffic demand based on the layered–graph and a given cost function. It finally outputs a physical topology.

This thesis 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 Section 4, we show the numerical results obtained through simulations and evaluate the proposed scheme. In Section 5, we present our conclusions and directions for a future work.

2 Planning and Designing Robust WDM Network

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. Figure 1 is an example. Each WDM node equips with MUXs/DEMUXs (multiplexers and demultiplexers) and OXCs as depicted in Fig. 2. 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 described in Fig. 2, 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 (Fig. 1), we set up lightpaths for traffic demand in node–pairs. The lightpaths are configured over the WDM physical topology as shown in Fig. 3. Viewed from the upper layer of the optical layer (e.g., IP layer), the nodes are directly connected via the lightpath (Fig. 4). We call a set of lightpaths the *logical topology*.

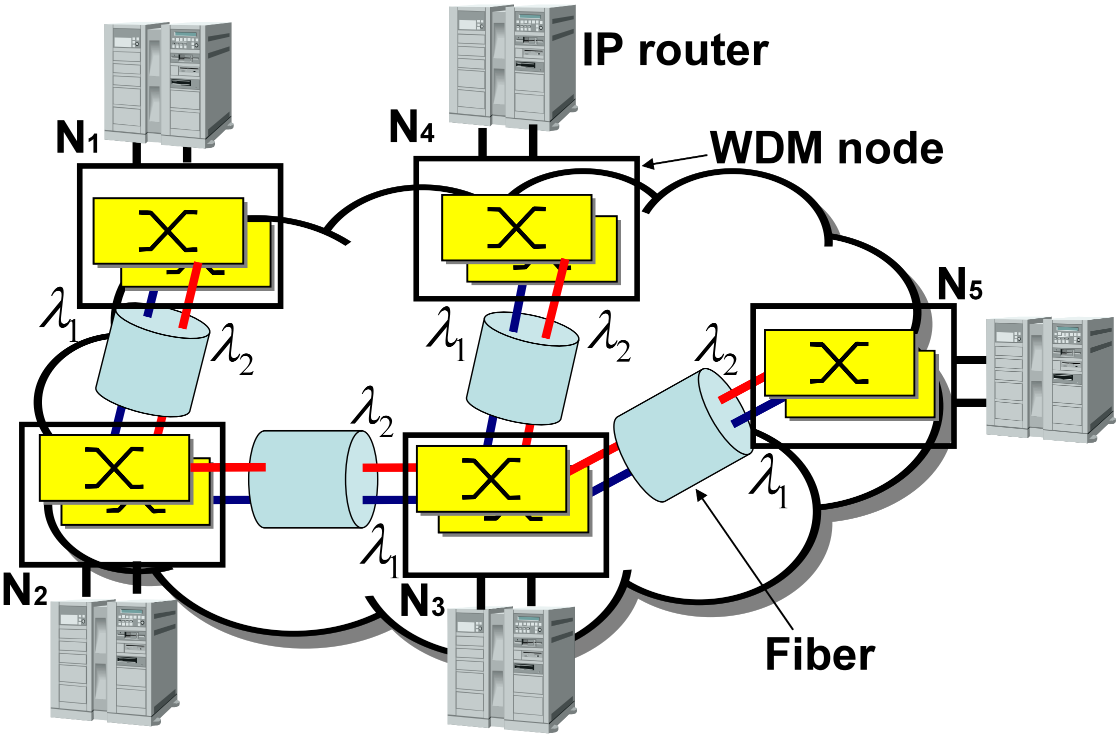

Figure 1: A WDM physical topology

2.2 Planning WDM Network

As we mentioned, we will design a robust WDM networks subject to 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 planning cost (i.e., 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 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 may 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

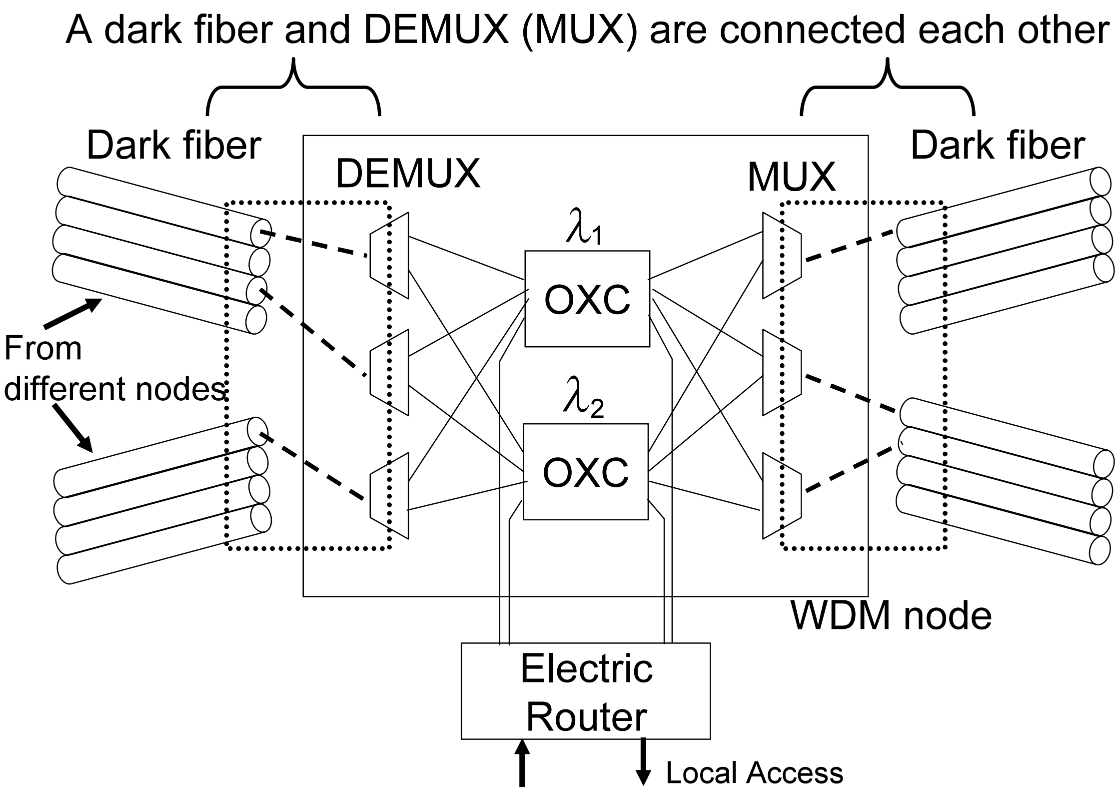

Figure 2: WDM node architecture

fibers. The assumption is the most general and it is quite valid when we treat wavelengths in a single waveband like center waveband (C-band) between 1530 nm and 1560 nm. When we use L-band (1560 – 1600 nm) or S-band (1490 – 1530 nm) that require different optical amplifiers used in C-band, we should treat different number of wavelengths as described in Refs. [11, 12, 13].

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

- We deploy only 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

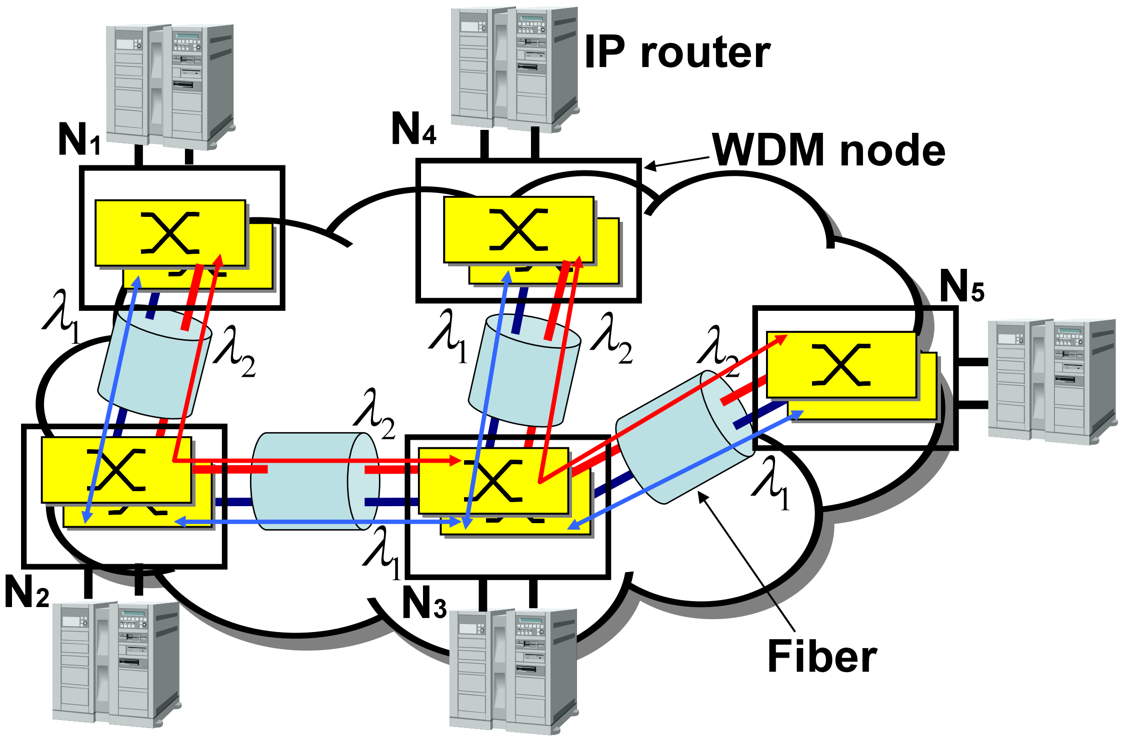

Figure 3: Configuring lightpaths over a physical topology

4×4 OXCs. As a result, we can decrease the number of OXCs which the operators maintain.

- We keep identical the number of OXC ports for each wavelength on a WDM node. When we require additional ports to an OXC switching a certain wavelength, we add OXCs for the other wavelengths on the node by the same number of ports.

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

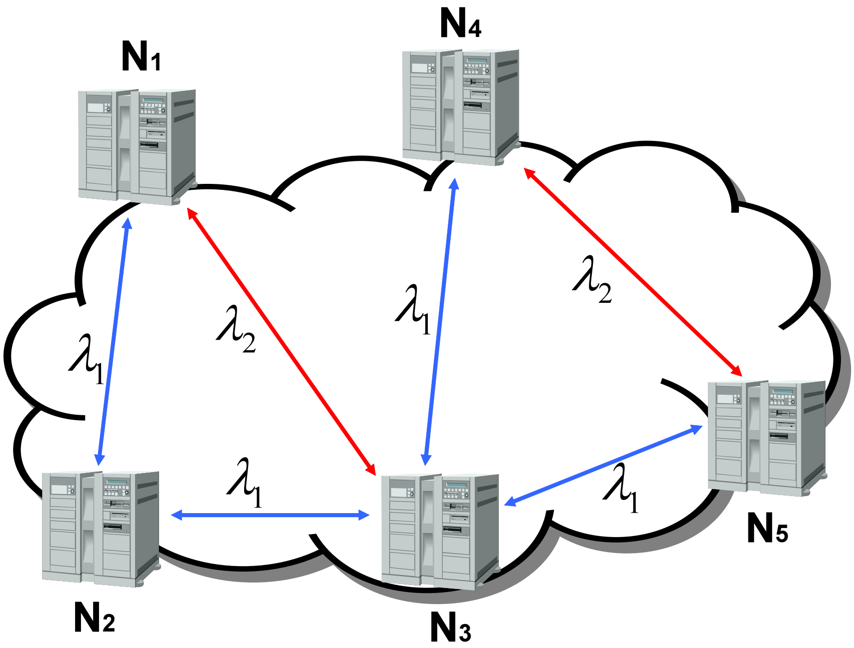

Figure 4: A logical topology

such a network is to deploy redundant resources to all links and nodes (e.g., 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 (e.g., normal distribution or exponential distribution). Since actual traffic dynamically changes, on the other hand, the actual traffic will follow a certain distribution. A real problem is that we have no ways of knowing which distribution the traffic will follow.

In this thesis, we assume that the discrepancy between the volume of traffic actually occurring and the predicted volume will follow a normal distribution. 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 thesis, “traffic change” does not refer to the change of traffic demand in a short time (e.g., 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 each of that follows a normal distribution based on a predicted traffic and utilizes it as an input parameter of the WDM network design problem. Each traffic demand is expressed as a traffic matrix. A 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 random variable following 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. Even if the traffic change does not follow a normal distribution, we believe that our method can accommodate the traffic demand as long as the prediction of the future traffic is accurate to some extent.

3 Robust WDM Networks Subject to Traffic Changes

The objective of our design method is to design WDM networks that are robust against *traffic changes*. In this section, We will first describe outline of our scheme based on ADD algorithm. We then describe each subproblem shown in the outline.

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 consists of the following two subproblems. We handle them repeatedly by using ADD algorithm (Fig. 5).

(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 cost-effectively, we extend appropriate OXCs based on an ADD algorithm (ADDA) by extending the traditional ADD algorithm [8] The point of our idea is to add the given number of ports of the new OXCs to the WDM nodes such that the designed network could accommodate as much uncertain traffic as possible.

(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.

The traditional ADD algorithm was proposed to resolve the warehouse deployment problem [8]. In the traditional algorithm, the iteration of adding a warehouse is continued

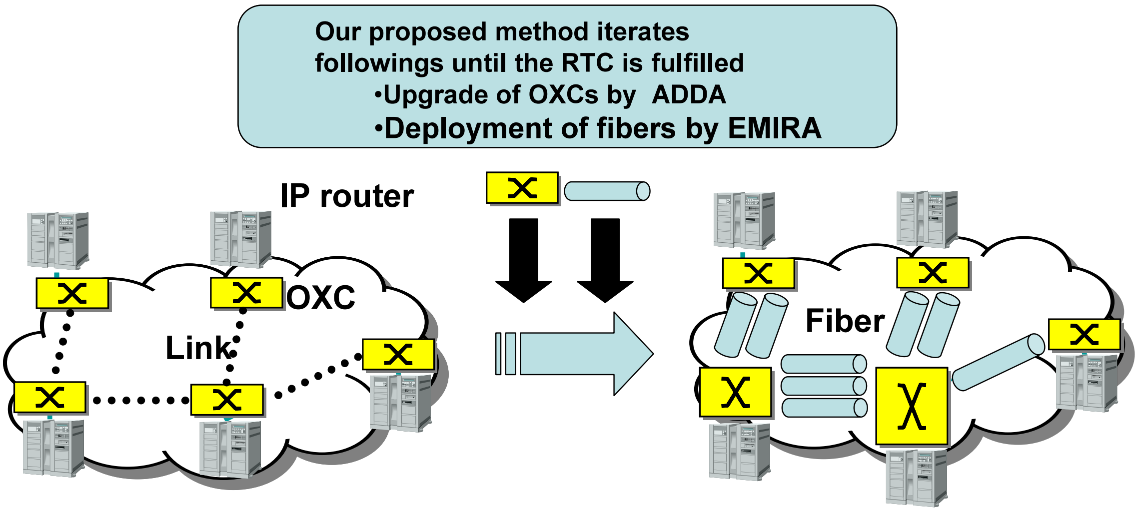

Figure 5: Outline of WDM network design

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 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.

$\bar{\boldsymbol{T}}^{(x-1)}$: A matrix each element of which represents the average volume of traffic demand in the previous period, $\bar{t}_{ij}^{(x-1)}$.

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

$\boldsymbol{\Sigma}^{(x)}$: A matrix each element of which represents a standard deviation, $\sigma_{ij}^{(x)}$. It determines how the traffic demands between nodes i and j changes 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 $\mu_{ij}^{(x)} = \alpha^{(x)} \times \bar{t}_{ij}^{(x-1)}$.

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 a node k that satisfies Eq. (1). In Section 3.2, we describe it in more detail.

Step (3-b): Lease fibers. Input K traffic patterns from T_0 through T_{K-1} and try to accommodate traffic demand of them that are still not accommodated in the previous iteration using EMIRA (see Section 3.3). Set b_i to the number of lightpaths that cannot be accommodated when the traffic pattern is T_i.

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

Using Step (1), we roughly predict K traffic patterns $\boldsymbol{T}_0, \ldots, \boldsymbol{T}_{K-1}$ assuming that the traffic increases at a regular rate [7]. In Step (2), we install a $p \times p$ non–blocking OXC for each wavelength on nodes. On the node that are 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 A 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. 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. Let M_{ij} denote the maximum flow value of node–pair (i, j). Traffic demand to a node–pair, the maximum flow value of which 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 maximum flow value to the expected volume of traffic demand ratio ratio is the lowest. This is achieved by expanding node k that satisfies the following equation.

$$\max_{k} \min_{i,j} (\frac{M_{ij}}{\mu^{x}_{ij}}). \tag{1}$$

For each wavelength at node k, we increase the number of OXC ports of upgradable OXCs by δ. The OXC extension prevents blocking in setting up a lightpath.

3.3 A 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. We propose EMIRA (Enhanced Minimum Interference Routing Algorithm) to achieve it. This is based on MIRA (Minimum Interference Routing Algorithm) [9], which is summarized in Appendix. Since in MIRA, a fixed physical topology is used as an input information we cannot apply it to our fiber deployment problem where the physical topology is the *output* information. In EMIRA, we use the layered-graph described in [14] instead of the physical topology. The layered-graph has W layers as shown in Figs. 6,7, where W is the number of wavelengths multiplexed. In the graph of the kth layer, a vertex (i.e., node) corresponds to an OXC for wavelength k and an edge (expressed as $e_{(index\_of\_link),(index\_of\_wavelength)}$ in Fig. 7) corresponds to a set of wavelength k's available resources between two OXCs. Each link cost is given by Eq. (2). If no wavelength k 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 are left for potential future traffic demand. In EMIRA, we assign a link cost expressed by Eq. (2) to each link on the layered-graph. It takes into account the remaining resources as well as *critical link*s. (The critical link is 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 [9].) EMIRA gives priority to determining a path that has many remaining resources by utilizing the amount of

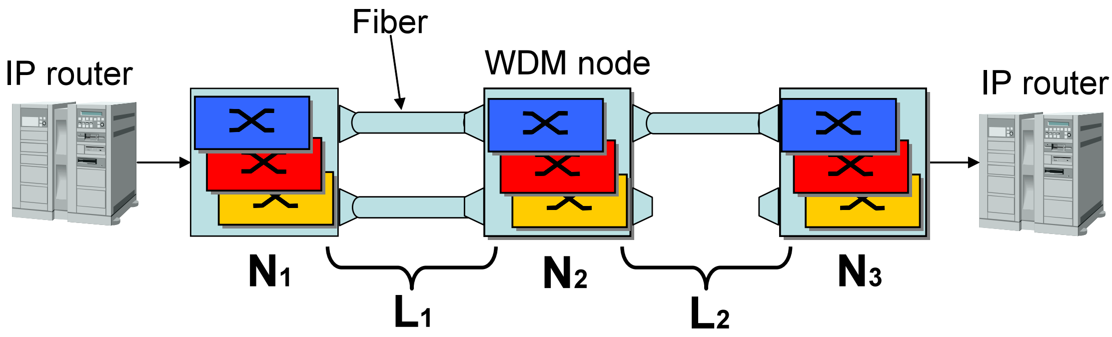

Figure 6: Original network of the layered graph

remaining resources as the denominator of link cost.

$$Cost_{ij} = \begin{cases} \infty & \text{if } B_{ij} = 0 \text{ and } C_{ij} = 0 \\ 0 & \text{if } A_{ij} = 0,\ B_{ij} \neq 0 \text{ and } C_{ij} = 0 \\ \dfrac{A_{ij}}{B_{ij} \times \frac{A_{ij}}{Q(Q-1)} + C_{ij}} & \text{otherwise} \end{cases} \quad (2)$$

where

A_{ij}: Number of node–pairs that regard wavelength j on link i as *critical link* (we explain how to calculate A_{ij} in 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 $C_{ij} = 0$, link cost of wavelength j on is given infinity because there is no wavelength to set up lightpaths. When $A_{ij} = 0$, $B_{ij} \neq 0$ and $C_{ij} = 0$, link cost

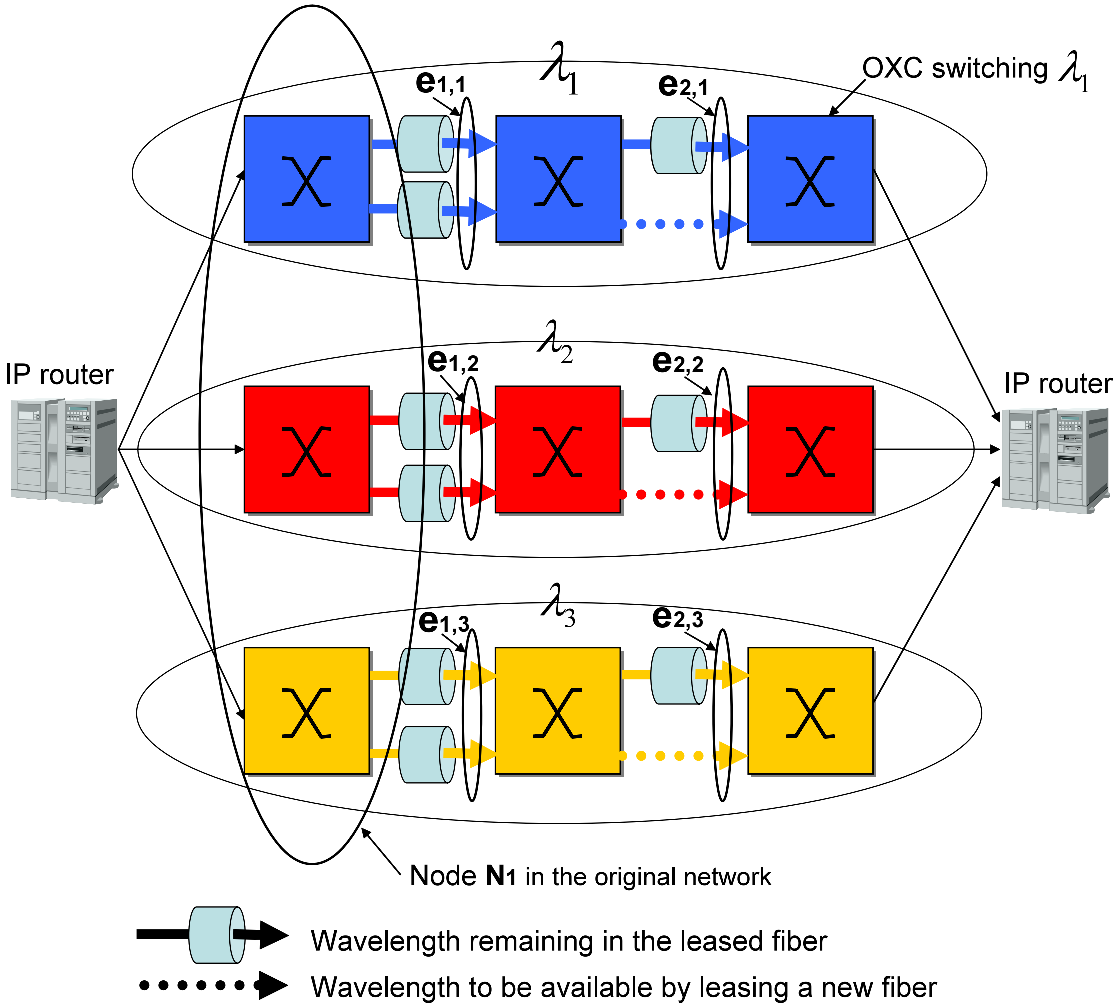

Figure 7: Example of layered graph: The number of wavelengths = 3

of wavelength j on link i is 0 because there are wavelengths to be remaining by leasing new fibers and no node–pair regards it as critical link.

By introducing B_{ij}, we place priority on selecting a route where more OXC ports are remaining. But we do not simply use the number of remaining OXC ports as link cost. Instead, we introduce the 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 many remaining OXC ports in the congested link while we should keep remaining OXC ports for the future traffic demand in the link which is not congested. The congested link is defined as the link that many node–pairs regard as 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.

EMIRA outputs the following; where to route a lightpath, which wavelengths to assign to the lightpath, where to lease dark fibers and how many dark fibers to lease. 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 of a lightpath, we can always set up the lightpath.

INPUT

- Layered-graph that consists of existing OXCs and 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.
- Number of fibers necessary in each link to accommodate traffic.

ALGORITHM

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

Step (1-a): Calculate the maximum flow of each source–destination pair except (s, t) by using the Fold–Fulkerson algorithm [15] and obtain critical links for each source–destination pair.

Step (1-b): Calculate A_{ij} using MIRA (See 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. 2.

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 Models

We use a 15–node network model that is shown in Fig. 8. There initially exists no fiber on each link. When we need fibers, we lease dark–fibers on a link. The traffic demand occurs at each node–pair uniformly. 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 by our scheme with the one designed for minimizing the OXC cost. As such a network, we use the one designed by the heuristic optimization method [16]. The heuristic optimization method 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), LLR (Leased Loaded Routing)). Then, the network is globally optimized by trying to reroute the traffic demand. The heuristic optimization method has shown to be a superior algorithm which obtains suboptimal results with less computational effort than the ILP (Integer Linear Programming). We use MIN-HOP in the heuristic optimization method. We call those two networks as follows.

PT_{ADD} : Network designed by our proposed scheme for robustness against the traffic changes.

$PT_{min-cost}$: Network designed by Heuristic Optimization Method (HOM) for minimizing the OXC cost.

When the traffic demand actually occurs, we must determine on which route to accommodate it. Since the actual traffic demand occurs dynamically, the route assumed to accommodate the traffic demand in design step can be different from the route which actually accommodate it. As a routing algorithm, We use MIRA [9] for both PT_{ADD} and $PT_{\mathrm{min-cost}}$ because MIRA can accommodate as much unpredicted traffic as possible.

4.2 Evaluation Results

We first evaluate the performance of PT_{ADD} and $PT_{\mathrm{min-cost}}$ when the predicted traffic demand actually occurs. We express the predicted traffic as a traffic matrix, $\boldsymbol{T}_0 = \{\mu_{ij}\}$. The μ_{ij} is the traffic volume requested by node–pair (i, j). Figure 9 shows the total OXC cost required when each method designs a network. We calculate the cost of $v \times v$ OXC as $\frac{v}{2} \log_2 v$, assuming that the OXCs are implemented as a multistage interconnection network [5]. The OXC cost value in the graph represents the relative value to the cost of an 8×8 OXC. In $PT_{\mathrm{min-cost}}$, OXC cost is calculated only based on the number of ports actually used. The horizontal axis is the number of traffic matrices that are used by each design method. The OXC cost value at k-th index of the horizontal axis shows the cost each method needs to design the network which accommodate k traffic matrices (from $\boldsymbol{T}_0$ to $\boldsymbol{T}_{k-1}$). t_{ij}^k, each element of $\boldsymbol{T}_k$, is a random variable that follows a normal distribution, $N(\mu_{ij}, (\sigma)^2)$. In Fig. 9, we use $\mu = 1$ and $\sigma = 0$, that is, a traffic matrix where each node–pair uniformly requires one lightpath repeatedly for the design. In Fig. 9, the OXC cost of PT_{ADD} increases in spite that the identical traffic matrix is repeatedly inputted. This is because in our proposed method, EMIRA may determine the route for each traffic demand different from the route the previous traffic matrix is inputted according to the amount of resources remaining in the time of the traffic being inputted. The cost of PT_{ADD} is 213, which is twice as much as that of $PT_{\mathrm{min-cost}}$, 102. We show cost in Fig. 10 when we use $\mu = 2$ and $\sigma = 0$. The cost of PT_{ADD} and $PT_{\mathrm{min-cost}}$ are 490 and 264, respectively.

We next evaluate how much traffic demand is blocked in PT_{ADD} and $PT_{\mathrm{min-cost}}$ when predicted demand occurs. When the route information of all lightpaths for predicted traffic at the design phase is hold, we can actually assign all the lightpaths in the network designed from both our proposed method and the heuristic optimization method. However, the point of this thesis is to consider that the requested demand may be different from the demand we predicted. We thus assign lightpaths according to the MIRA policy which maximize the volume of traffic accommodate in the future.

Figures 11 and 12 show the ratio of blocked lightpaths when the predicted traffic occurs in PT_{ADD} and $PT_{\mathrm{min-cost}}$. The horizontal axis shows the index of traffic matrix that actually occurs. Note that σ equals to 0, all the traffic matrices actually occurring are identical. But in the network design for each traffic matrix, the order of the node–pair that is assigned to lightpaths is randomly determined. n is the number of traffic matrices used to design the network. In $PT_{\mathrm{min-cost}}$, the ratio of blocked lightpaths are between 0.17 and 0.22 when we use $\mu = 1$, and are between 0.15 and 0.17 when we use $\mu = 2$ although the predicted traffic actually occurs. This is because routes of lightpaths selected in designing the $PT_{\mathrm{min-cost}}$ are different from those routes that are determined for accommodating the actual traffic demand. In PT_{ADD}, the ratio of blocked lightpaths are between 0.04 and 0.08 ($\mu = 1$) and are between 0.03 and 0.06 ($\mu = 2$) when $K = 1$. All the requests are accommodated when K is 10 and 20. This is because our proposed method selects the routes taking into account the routes on which the actual traffic demand is accommodated in the design step.

We next show the evaluation results when the actual traffic demand is not just same as predicted one (i.e., σ is not equal to 0) but it follows a predicted distribution. Here, the predicted distribution means that μ and σ of traffic demand actually occurring are same as μ and σ of traffic demand used to design a network. The original heuristic optimization method does not consider the case where traffic demand actually occurring changes. We modify the original heuristic optimization method to accommodate the traffic changes. When K different traffic matrices are inputted, the modified heuristic optimization method first generates a traffic matrix, $\boldsymbol{T}_{\max}$. $\boldsymbol{T}_{\max}$ is a traffic matrix each element of which, $t_{ij}^{\max}$, equals to the maximum traffic volume of node–pair (i, j) among K traffic matrices ($t_{ij}^{max} = \max_k(t_{ij}^k), (k = 0, 1, 2, \ldots, K-1)$). The modified heuristic optimization method, then, designs a network that accommodates $\boldsymbol{T}_{\max}$ with minimum OXC cost. We call the network designed by the modified heuristic optimization method as $PT_{\text{modified}-\text{hom}}$. Figures 13 through 16 show the OXC cost of PT_{ADD} and $PT_{\text{modified}-\text{hom}}$ when we use $\mu = 1, 2$ and $\sigma = 1, 2$ respectively. Note that the cost of $PT_{\text{modified}-\text{hom}}$ exceeds that of PT_{ADD}. We can say that it is redundant trying to accommodate the maximum traffic volume of predicted traffic matrices, $\boldsymbol{T}_{\max}$. The difference of those cost gets larger as the traffic change goes large ($\sigma = 2$). The cost of $PT_{\text{modified}-\text{hom}}$ does not keep increasing although $\boldsymbol{T}_{\max}$ keeps growing as the number of inputted traffic matrices increases. This is because an 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.

Figures 17 through 20 show the ratio of blocked lightpaths when the traffic demand actually occurring is not just same as predicted one but it follows as the predicted distri-

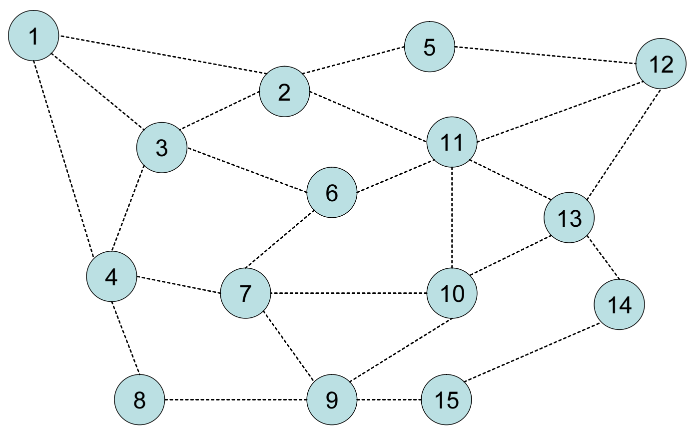

Figure 8: Network model

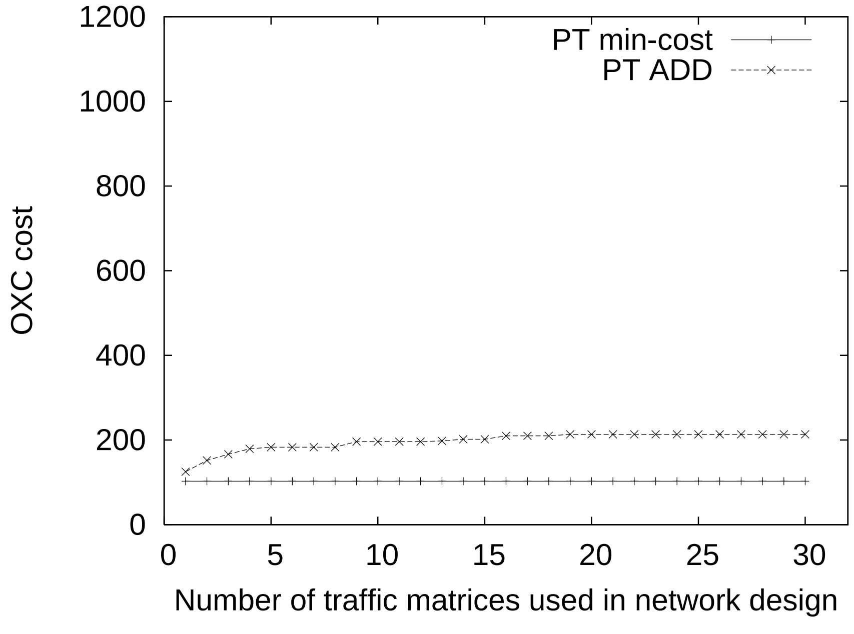

Figure 9: OXC cost (traffic $\mu = 1, \sigma = 0$)

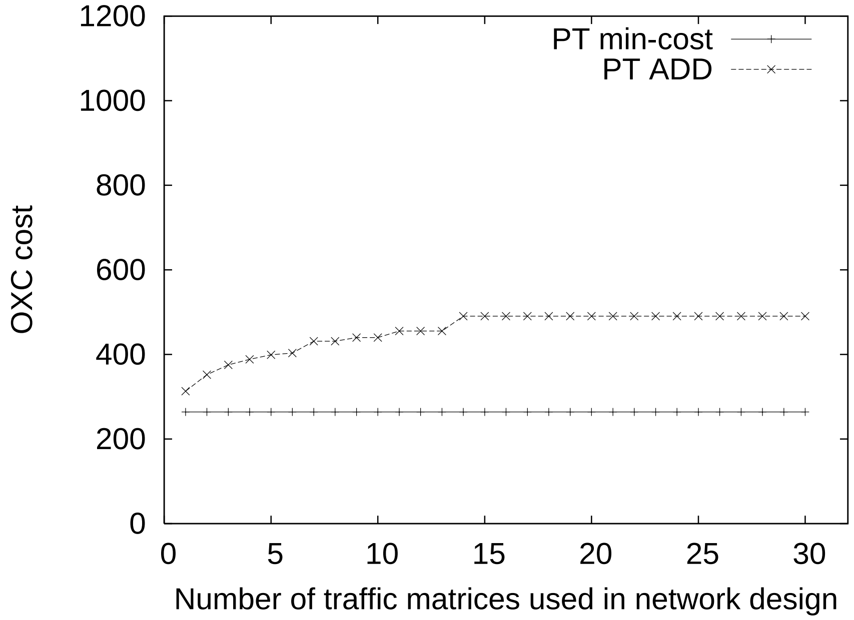

Figure 10: OXC cost (traffic $\mu = 2, \sigma = 0$)

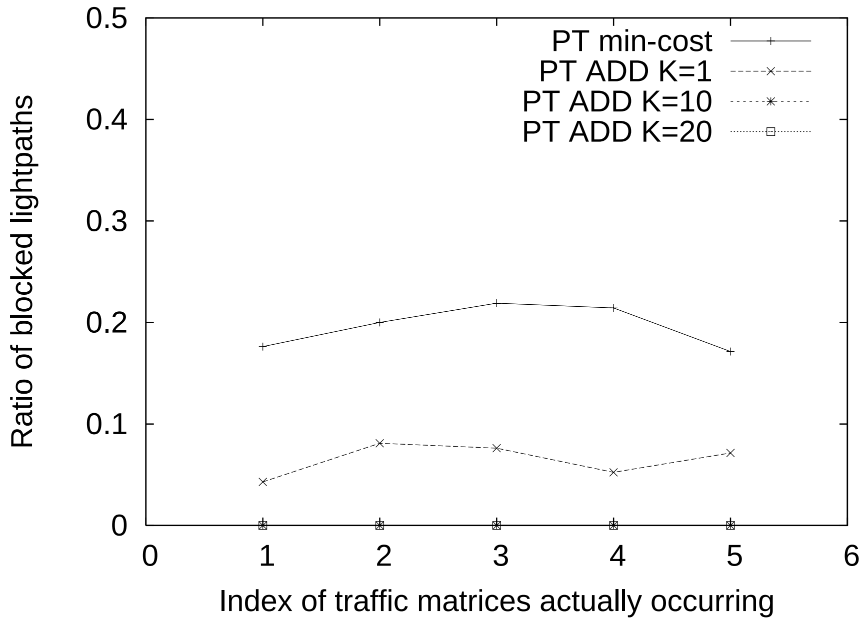

Figure 11: Ratio of blocked lightpaths (traffic $\mu = 1, \sigma = 0$)

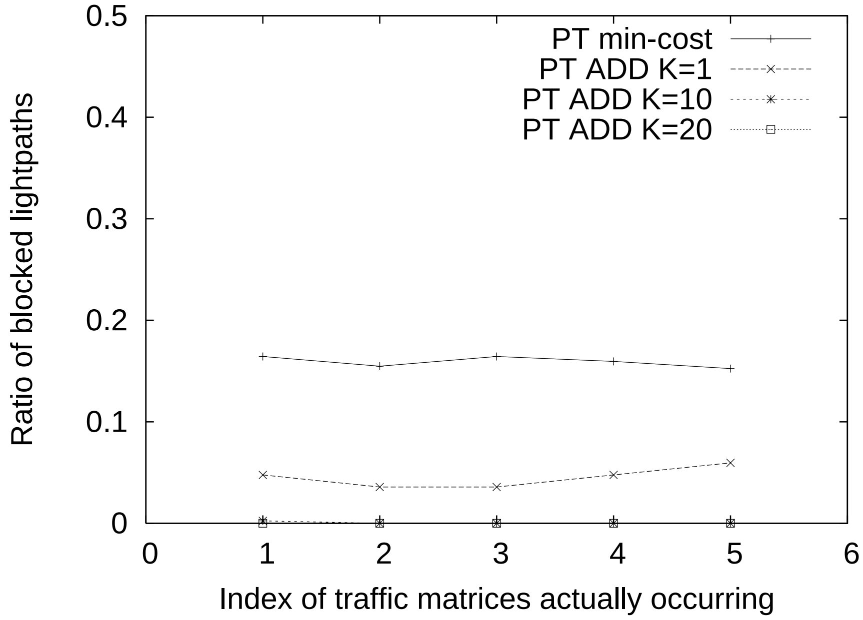

Figure 12: Ratio of blocked lightpaths (traffic $\mu = 2, \sigma = 0$)

bution. When we use 10 traffic matrices in both methods ($K = 10$), no traffic demand is blocked in PT_{ADD} while some traffic demand is blocked in $PT_{\mathrm{modified-hom}}$ (see first and fifth index of traffic matrices in Fig. 19, first and second index of traffic matrices in Fig. 20). PT_{ADD} can accommodate more traffic than $PT_{\mathrm{modified-hom}}$ while PT_{ADD} needs less OXC cost than $PT_{\mathrm{modified-hom}}$.

To evaluate how cost–effectively our method uses the network equipment, we compare PT_{ADD} with $PT_{\mathrm{modified-hom}}$, both of which are designed with the same OXC cost. For this purpose, we selected PT_{ADD} designed with $K = 20$, $\mu = 2$, and $\sigma = 1$ and $PT_{\mathrm{modified-hom}}$ designed with $K = 7$, $\mu = 2$, and $\sigma = 1$. The former costs 498 and the latter does 508. Figure 21 shows the ratio of blocked lightpaths in the PT_{ADD} and in the $PT_{\mathrm{modified-hom}}$ when the actual traffic follows $N(2, 1^2)$ normal distribution. No blocking occurs in PT_{ADD} while the blocking occurs in half of all the traffic demands in $PT_{\mathrm{modified-hom}}$.

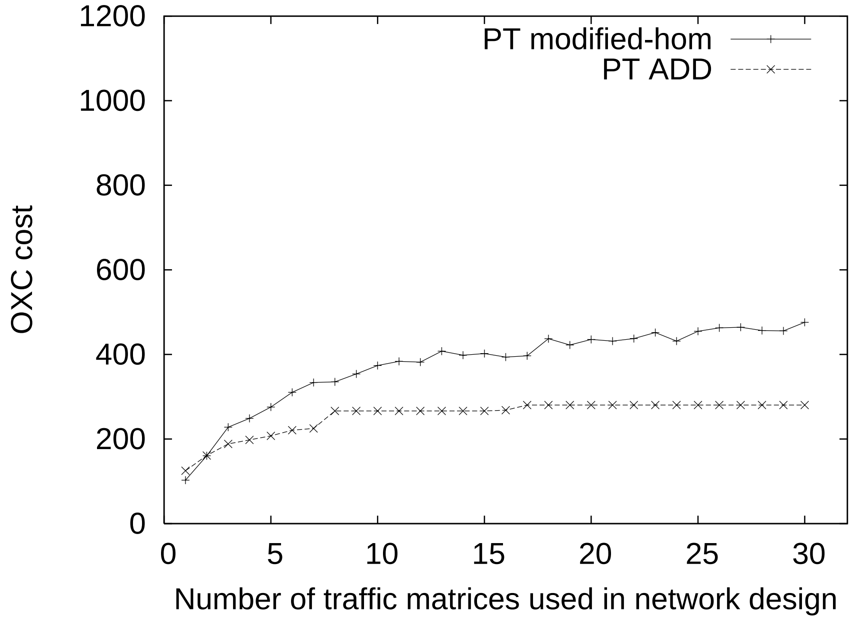

Figure 13: OXC cost (traffic $\mu = 1, \sigma = 1$)

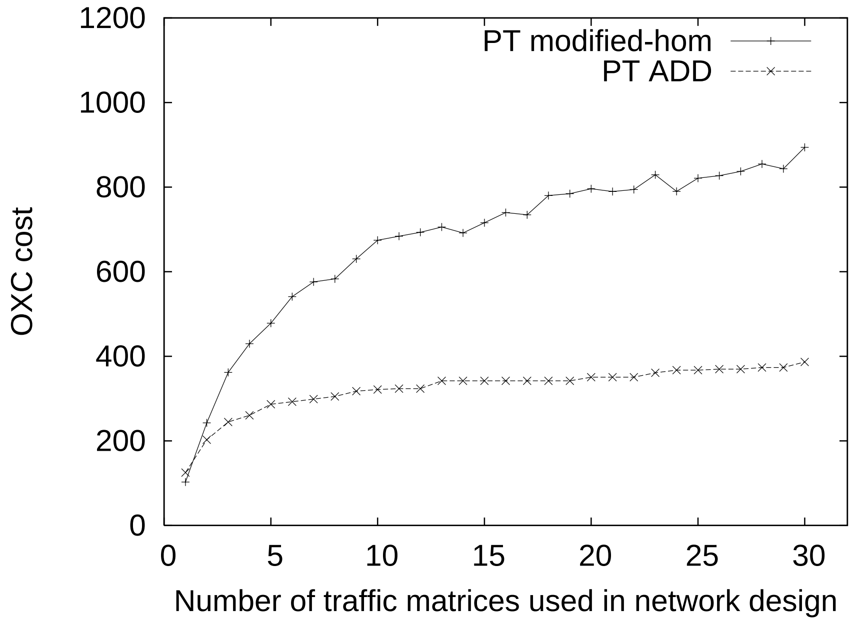

Figure 14: OXC cost (traffic $\mu = 1, \sigma = 2$)

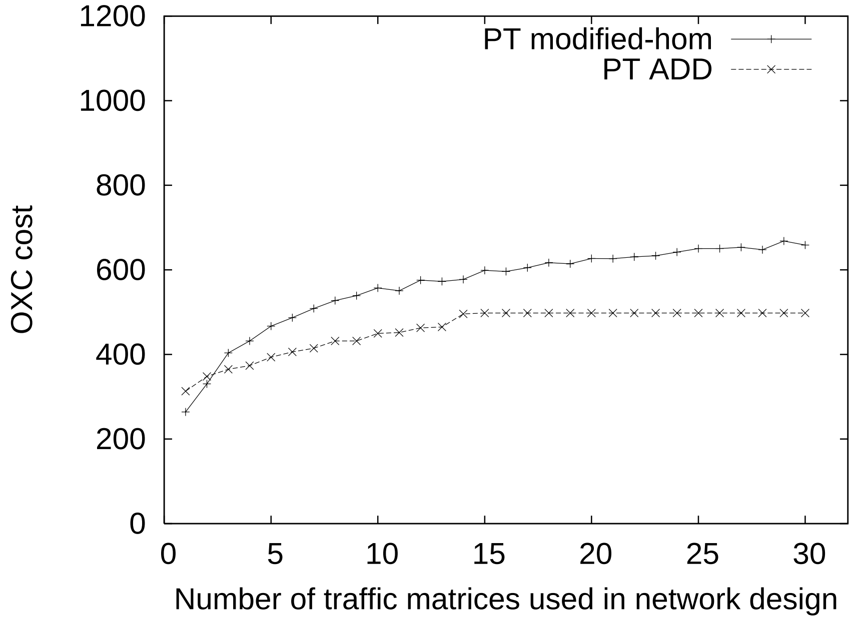

Figure 15: OXC cost (traffic $\mu = 2, \sigma = 1$)

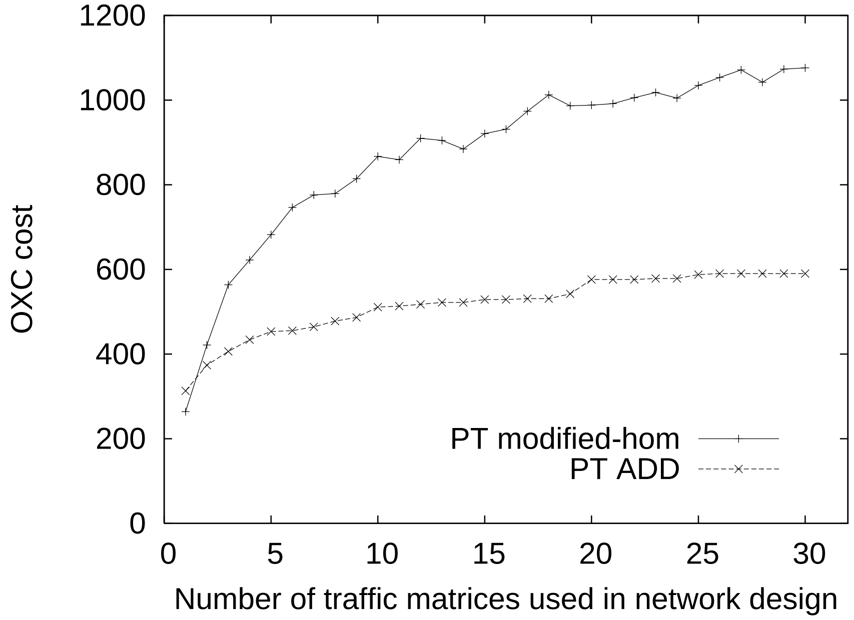

Figure 16: OXC cost (traffic $\mu = 2, \sigma = 2$)

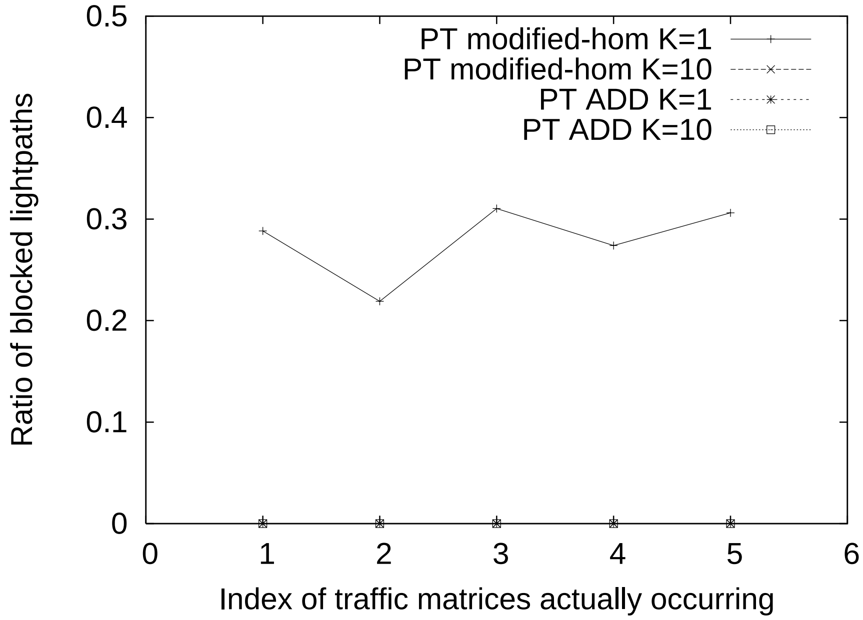

Figure 17: Ratio of blocked lightpaths (traffic $\mu = 1, \sigma = 1$)

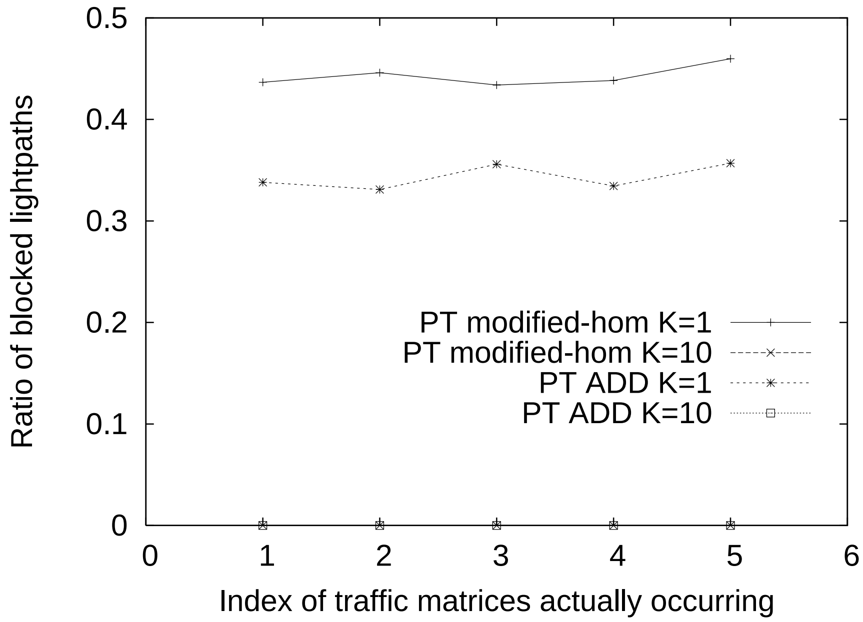

Figure 18: Ratio of blocked lightpaths (traffic $\mu = 1, \sigma = 2$)

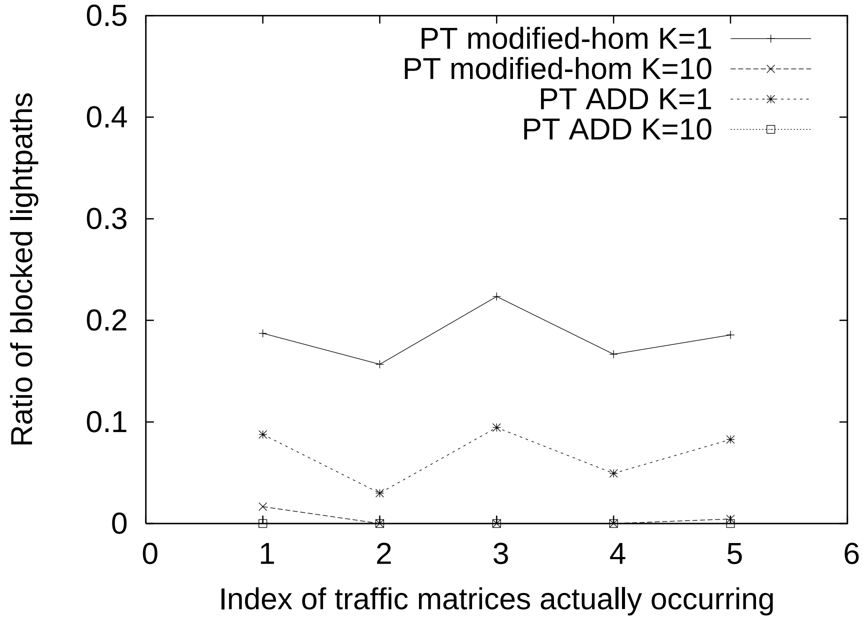

Figure 19: Ratio of blocked lightpaths (traffic $\mu = 2, \sigma = 1$)

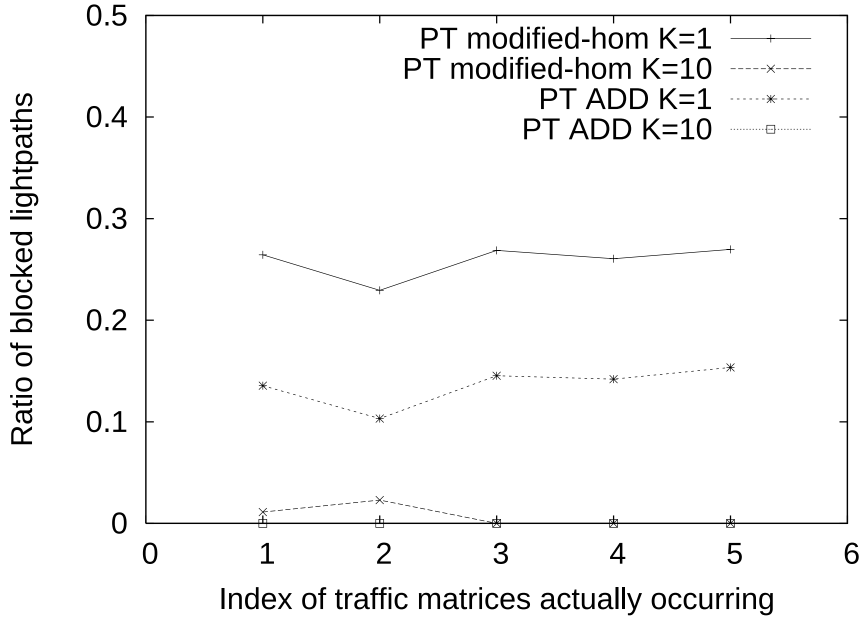

Figure 20: Ratio of blocked lightpaths (traffic $\mu = 2, \sigma = 2$)

We finally compare our design method with over–provisioning approach. Over–provisioning is a simple way to design a network which can accommodate more traffic demand than the predicted traffic demand. Now we assume the situation we predict occurrence of traffic demand that follows $N(2, 1^2)$. In this situation, our method designs a network with traffic matrices which follow $N(2, 1^2)$ while the heuristic optimization method for over–provisioning designs a network that can accommodate more traffic volume than 2 in each node–pair. Figures 22, 23 show the ratio of blocked lightpaths of PT_{ADD} with $K = 21$, $\mu = 2$ and $\sigma = 1$ and PT_{HOM} with $K = 1$, $\mu = 3$ and $\sigma = 0$, both of which cost 451. We assume the traffic demand actually occurring to be follow $N(2, 1^2))$ in Fig. 22 and $N(2, 2^2)$ in Fig. 23 (i.e., traffic changes are larger than predicted) respectively. PT_{ADD} shows lower ratio of blocked lightpaths than PT_{HOM} in both Figs. Our method uses the network equipment more efficiently than over–provisioning approach.

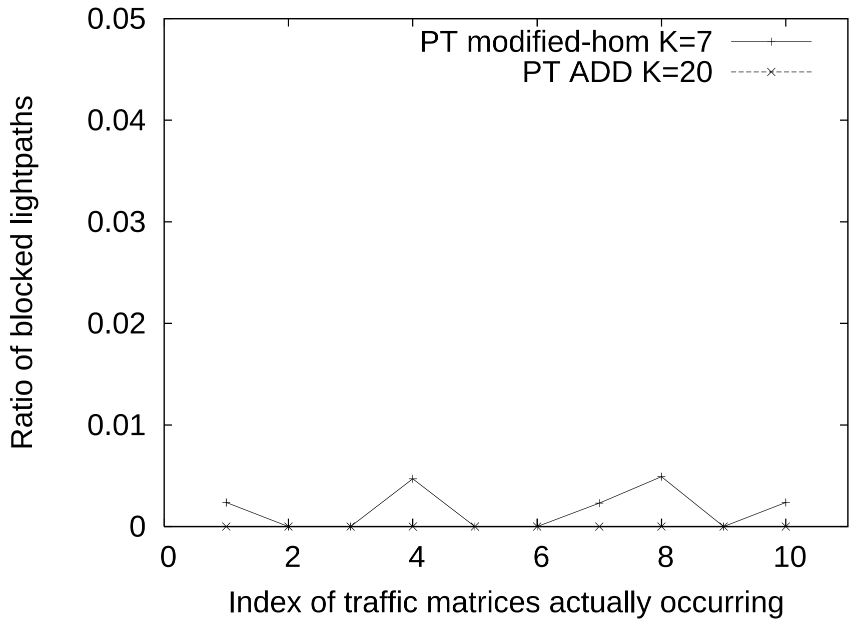

Figure 21: Ratio of blocked lightpaths (OXC cost PT_{ADD} : 498, $PT_{\mathrm{modified-hom}}$: 508, traffic $\mu = 2, \sigma = 1$)

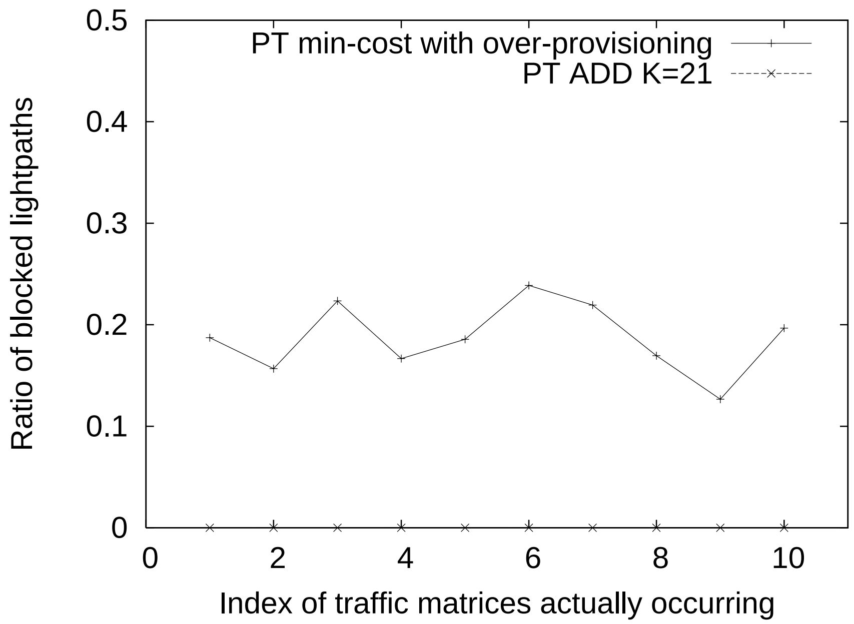

Figure 22: Ratio of blocked lightpaths (OXC cost: 451, traffic: $\mu = 2, \sigma = 1$)

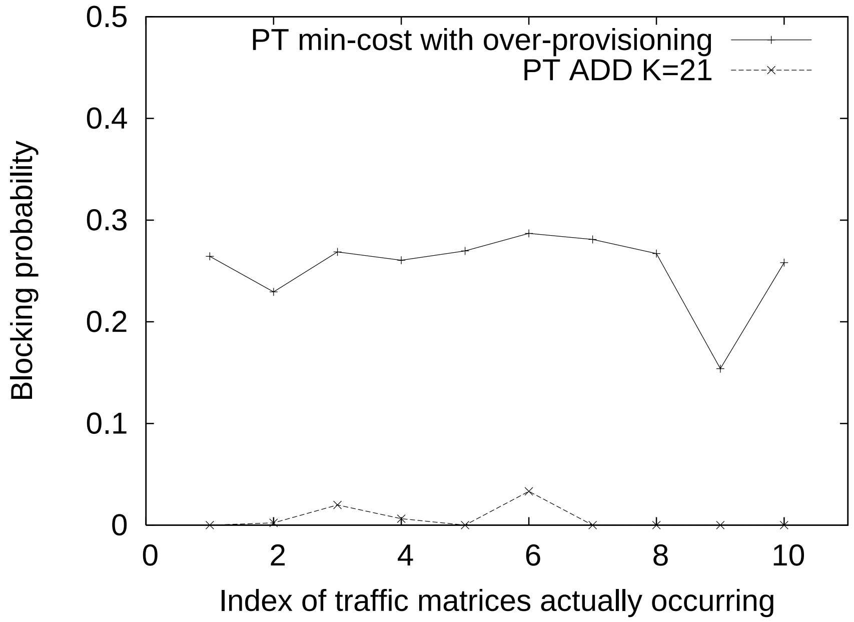

Figure 23: Ratio of blocked lightpaths (OXC cost: 451, traffic: $\mu = 2, \sigma = 2$)

5 Conclusion

In this thesis, we have proposed a novel design method of WDM network that is robust against traffic changes. We have first defined the condition that a robust WDM network needs to fulfill. The condition is to have an ability to accommodate some numbers of traffic matrices which we generate under the assumption that they follow a certain distribution (e.g., a normal distribution). The network design problem is devided into two subproblems, *OXC–deployment problem* and *fiber–deployment problem*. We repeatedly handled these two subproblems based on ADDA. In the *OXC–deployment problem*, we proposed a method to upgrade OXCs on the node. It maximize the traffic demand accommodated in the future. We also proposed EMIRA that determines where and how many fibers to lease so that the designed network accommodate as much unpredicted traffic as possible in *fiber–deployment problem*. Throughout the simulation, we have shown that the network designed by our proposed method can accommodate the predicted traffic demand dynamically occurring while the one designed by the existing method does not although our method costs twice as much as the existing one. Under the situation where traffic demand changes following our predicted distribution, the network designed by our proposed method can prevent traffic demand from being blocked with less cost than the one designed by the existing method. In addition, we evaluated how cost–effectively we use the network equipment. Using the same OXC cost, the network which our proposed method designs shows lower blocking probability than the one obtained by the over–provisioning approach. 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 to apply our proposed method to the multi–period network design. In the multi–period network design, It is important to determine how long the design period is (e.g., short term planning or long term planning) since the overall network cost is affected by reduction of WDM network components by the evolution of optical technology.

Appendix: MIRA (Minimum Interference Routing Algorithm)

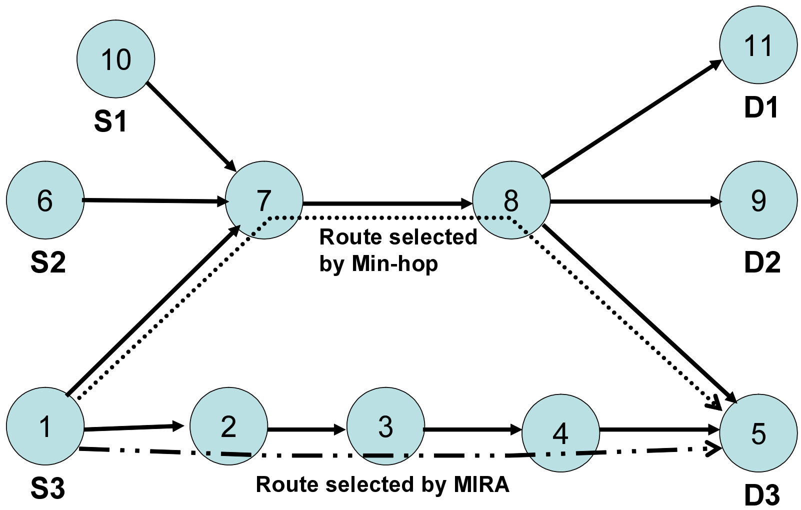

Figure 24: Routes selected by MIN-HOP and MIRA

Here we briefly discuss MIRA [9]. 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 24 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 maximum flow values are computed using the Fold-Fulkerson algorithm [15]. 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,

$$Cost_{ij} \quad = \quad A_{ij} = \sum_{s,d} x_{sd}^{ij} a_{sd}^{ij}, \tag{3}$$

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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