

# Quasi-Dynamic Network Design Considering Different Service Holding Times

Koichi Kanie, Hiroshi Hasegawa, *Member, IEEE*, and Ken-ichi Sato, *Fellow, IEEE*

**Abstract**—We propose a quasi-dynamic network design algorithm considering traffic growth in multi-layered photonic networks that consist of electrical paths and optical paths. The quasi-dynamic network design proposed herein leaves existing paths unchanged in order to minimize service disruption due to path rerouting as well as human error. Simulations verify that the network cost strongly depends on the network design algorithms adopted and the holding terms of service traffic. We, then, introduce a new parameter that represents expected service holding terms. The parameter is shown to represent effectively the network cost trend versus the number of the incremental designs. Furthermore, lower network cost is obtained by taking advantage of the network design algorithms that consider service holding times. This study is the first to address the criteria in designing future multi-layered photonic networks that offer cost-effective expansion while accommodating different services.

**Index Terms**—Multi-layered photonic network design, quasi-dynamic network design, service holding times, routing and wavelength assignment.

## I. INTRODUCTION

INTERNET traffic has been exploding [1] due to the rapid penetration of broadband access such as ADSL and FTTH. The current backbone networks mainly employ point-to-point WDM systems and electrical forwarding/routing systems. Therefore, they need O-E-O (optical-electrical-optical) conversion at intermediate nodes. The electrical processing and routing capability at nodes roughly doubles every eighteen months, i.e. Moore's law. As the traffic volume is increasing faster than processing capacity, the electrical bottleneck will become a serious problem [2]. In order to resolve this problem, photonic network technologies [3], [4] are being widely studied. In the photonic network, transport nodes are equipped with wavelength routing systems such as optical add/drop multiplexers and optical cross-connects (OXC) [5], in addition to electrical processing systems (Fig. 1). The OXCs route each optical path by using its wavelength information and do not require O-E-O conversion, except for when electrical regeneration is necessary. However there exists a strong constraint that connections using the same wavelength can not share a fiber. Finding proper routes and wavelengths satisfying the constraint for given connections is an important part of photonic network design [6]. The objective of network design is to minimize network (node plus link) cost and the problem

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The authors are with the Department of Electrical Engineering and Computer Science, Nagoya University, Nagoya 464-8603, Japan (e-mail: k.kanie@echo.nuee.nagoya-u.ac.jp, {hasegawa, sato}@nuee.nagoya-u.ac.jp).

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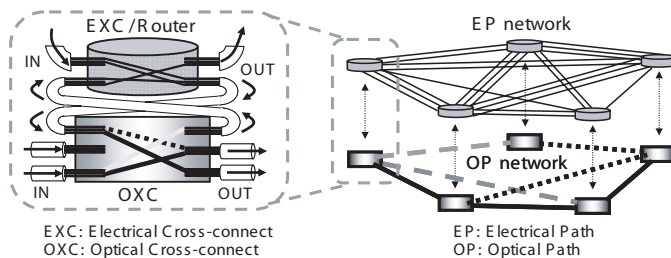


Fig. 1. Structure of multi-layered photonic network.

is known to be NP-complete [7]. Although the integer linear programming (ILP)-based approach [8] has been used to find optimal solutions, the problem is so computationally intensive that the heuristic approach is necessary to evaluate practical scale networks.

Conventional studies on photonic network design mainly fall into two categories: static network design [9]-[13] and dynamic network design [14]-[17]. In static design, a fixed traffic network is given and typically the target is to create a physical network that can minimize total network cost while accommodating the given traffic. In dynamic design, the amount of traffic is assumed to change dynamically, within seconds or minutes and the objective is the minimization of circuit/path connection blocking probability. Although the network traffic is rapidly increasing, as mentioned earlier, these conventional studies have not considered this condition.

A few studies [18]-[20] have discussed incremental traffic growth. One of them [18] investigates planning intervals for incremental traffic in SONET-based networks. The other study [19] shows that the major design challenge in minimizing the capital expenses of configurable optical networks is the uncertainty of traffic forecasts. The expenses predominantly consist of the cost needed to pre-deploy (or overprovision) resources in preparation for the expected future traffic demands. In [20], network design optimization for quasi-dynamic network design and parameter sensitivity analyses (ex. network topology, traffic growth rate, etc.) are discussed. The paper discussed a specific network design algorithm that always optimizes network cost at each design step without considering the spare capacity for future traffic demands. Furthermore, these studies assumed that existing traffic never disappear and incremental traffic volume is just added to it; service holding times are not considered.

In the real world, there are and will be many broadband services such as streaming video service, optical VPN service, optical leased line services, and broadband connections for e-science [21]. The holding times of these services will range

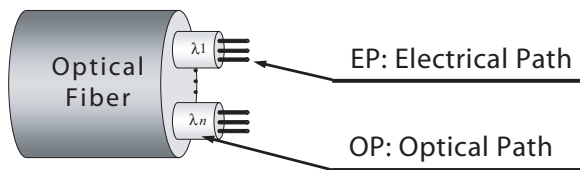


Fig. 2. Hierarchical path.

from hours/days to years/months and there may be little commonality. Therefore, a novel network design [22] must be developed that can not only consider continuous traffic increase, but also effectively accommodate widely divergent services with different holding times.

In this paper, we introduce quasi-dynamic multi-layered photonic network design algorithms that can cost-effectively accommodate the incremental traffic growth expected. First, we propose two distinctive quasi-dynamic design algorithms that can cope with traffic increases that are characterized by both service subscription rates and cancellation rates. We then analyze the network cost variations in terms of incremental traffic expansion. Since the network cost strongly depends on service traffic types that are accommodated, we then introduce a new parameter *Age*. This parameter is shown to represent the network cost trend versus the number of times the incremental design is implemented. Next, we further generalize the scheme so that it can handle multiple services with different holding times. We demonstrate the effectiveness of the proposed quasi-dynamic design algorithms through various simulations.

## II. QUASI-DYNAMIC NETWORK DESIGN

### A. Multi-Layered Photonic Network and Design Algorithm

Throughout this paper, we assume multi-layered photonic networks are used to create broadband networks cost-effectively. They consist of hierarchical paths with higher order path, optical paths (OPs), and lower order paths, electrical paths (EPs) such as LSPs (Label Switched Paths) in IP/MPLS and digital paths in SDH/SONET or OTN (Fig. 2). EP/OP's connection setup/release can be controlled [23] by using the ASON/GMPLS (Automatic Switched Optical Network [24] /Generalized Multi-Protocol Label Switching [25], [26]) protocol. In designing the photonic network, EPs are accommodated within OPs and are classified into two major groups: (1) those accommodated within an OP that connects directly the end nodes (source and destination nodes) of the EPs, and (2) those accommodated within concatenated multiple OPs. The former does not use expensive hardware such as O-E-O converters or electrical routing systems at intermediate nodes. If there is a sufficient number of EPs (traffic) to fill an OP, the cost can be minimized by using a direct OP. On the other hand, concatenated OPs generally achieve higher OP utilization and may reduce total hardware costs, particularly when the ratio of the total capacity of the EPs between the end nodes to the capacity of the OP is smaller than a specific value. Both of these OP configurations are adaptively utilized in the network design to minimize total cost [27], [28]. The resulting OP layer network is accommodated within a fiber network.

To accommodate the continuous traffic increases, periodic (every quarter or half year) expansion of the network is

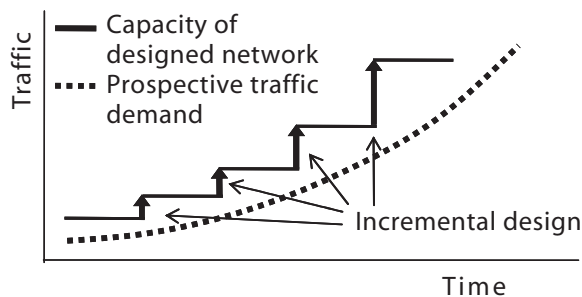


Fig. 3. Traffic growth and incremental design.

necessary (Fig. 3). The requirement for this expansion is that routes of existing paths should be left unchanged to minimize service disruption, any possible impairment, and processing complexity, which stems from path rerouting or from human-oriented errors. This requirement is particularly important for mission-critical services. Few papers have considered this incremental design problem, however; most focused on just one case where the existing paths never disappear and the traffic distribution is uniform.

In this paper, as a basis of the estimation of general long-term cost variation, we apply the following two simple algorithms to develop quasi-dynamic network design algorithms.

**Min-hop algorithm** All the EPs are accommodated within direct OPs that connect the end nodes of the EPs with the fewest hops possible. Even if only a single EP is demanded between a pair of nodes, this algorithm tries to set up a new OP. The usage of OPs, therefore, tends to be lower in the early network design stages where traffic volume is small. In subsequent network increment steps, however, the spare capacity is effectively used.

**Max-pack algorithm** This algorithm tries to minimize the total network cost at each incremental network design step by making the best use of the spare capacities of the existing OP network. The advantage of the Max-pack algorithm is that OP usage can be maximized. The disadvantage is that the average EP length increases.

In general, the combined design method using the above two algorithms will attain higher performance, however, the improvement achieved depends on the actual traffic characteristics. Details and benefits are demonstrated in Sec. III.C.

### B. Model of Traffic Variations

Current networks carry many types of traffics whose service holding times range from hours/days to years/months. Even if two traffic types have the same net increase rates (ex. 50% up per year), a difference in cancellation rates will yield different results (network cost). Therefore, it is essential to model the traffic changes to realize a network that well handles various service holding times. Incremental traffic growth can be characterized by two parameters, *a*: new service contract rate and *b*: service cancellation rate; the traffic growth rate is given as  $a - b$ . We designed a network using the two algorithms given in Sec. III.C employing different values of *a* and *b*.

In order to create a generalized method of estimating the cost variations after repetitive network expansion, we introduce and define the parameter  $Age(n)$ , which represents the

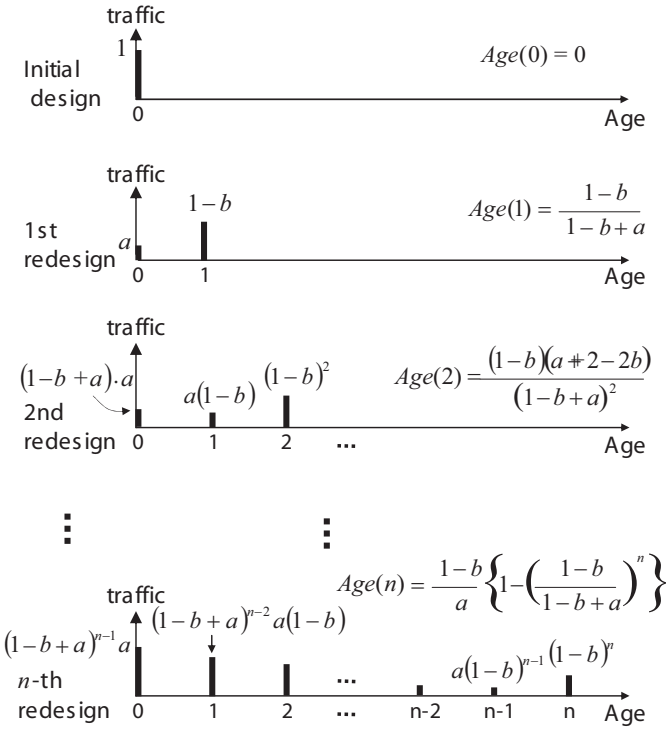


Fig. 4. Variation of Age at each redesign.

average age of the existing traffic just after the  $n$ -th network re-design. As shown in Fig. 4, for example, just after the 1st network redesign, the ratio of surviving initial traffic to the initial volume is  $1-b$  and that of added traffic is  $a$ . Here, ages of the added traffic distribute between 0 and 1, but they are all set at 0 for simplicity (ages are expressed as integer values). Therefore the average age,  $Age(1)$  is  $(1-b)/(1-b+a)$ .  $Age(n)$  is thus defined by

$$Age(n) := \frac{1-b}{a} \left\{ 1 - \left( \frac{1-b}{1-b+a} \right)^n \right\}.$$

We deduce that  $Age(m) < Age(n)$  ( $m < n$ ) and

$$\lim_{n \rightarrow \infty} Age(n) = \frac{1-b}{a} =: Age^*.$$

The importance of this parameter will be demonstrated in Sec. III.B.

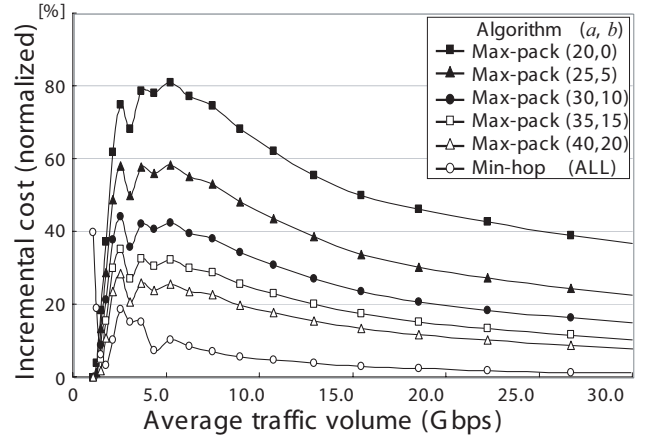
### III. NETWORK DESIGN RESULTS AND EVALUATIONS

We assume the following conditions for numerical experiments on the proposed quasi-dynamic network design.

#### Conditions

- Capacity of EP: 100 Mbps (set constant for simplicity)
- Capacity of OP: 2.5 Gbps (OC-48)
- WDM: 16 wavelengths per fiber
- Link: unidirectional link
- OXC nodes: no wavelength conversion (WP [4])
- OXC, EXC, and link costs: see Appendix
- Physical network topology:  $m \times m$  polygrid

In the design, the new EP demands anticipated are accommodated without changing the status of existing EPs and OPs at each increment as mentioned earlier. The traffic


 Fig. 5. Network cost with different contract/cancellation rates ( $a-b = 25\%$ ).

increase is given by that of the EPs for simplicity in the following evaluations. A traffic increase in the number of OPs is easily included by subtly modifying the algorithms. The total network cost consists of node and link costs as seen in the Appendix. The initial and incremental traffic demands are set to be randomly distributed in the network. The costs of the obtained networks are normalized by those calculated using a static zero-based design with the Max-pack algorithm. The static zero-based design provides network cost as designed from scratch, or it imposes complete traffic reconfiguration. It provides an ideal design in terms of cost.

#### A. Network Cost Variations for Quasi-Dynamic Design

Figure 5 shows the obtained normalized network costs against the average traffic between nodes for the Max-pack and Min-hop algorithms. The large average traffic volume corresponds to a large number of network re-designs. Each data point represents normalized incremental cost after incremental design. The initial traffic, average EP traffic between each node pair, is set at 1.0 Gbps, and the net traffic growth,  $a-b$ , is set at 25% while  $a$  and  $b$  are changed.

As for the Min-hop algorithm, the results are all the same for all different  $a$  and  $b$  values; incremental costs finally approach zero. On the other hand, the Max-pack algorithm has completely different behavior from the Min-hop algorithm and it strongly depends on  $a$  and  $b$  values. At the first design step (initial traffic), the Max-pack algorithm provides almost ideal cost; it is 40% smaller than that of the Min-hop algorithm. However, the advantage rapidly decreases and the reversal occurs at the fourth step. This is because the Max-pack algorithm tries to minimize the cost at each design point using the existing spare OP network capacity. This results in an increase in the average EP lengths and the increase degrades the network accommodation efficiency in subsequent steps. On the other hand, the Min-hop algorithm gives a larger incremental cost during some of the initial steps, and it approaches zero after many re-designs. This is because the Min-hop algorithm requires more OPs in the early stages, but the spare capacity is effectively used in subsequent steps. Fig. 6 and 7 show the network cost variations where  $a-b$  is 20% and 30%, respectively. Smaller values of  $a-b$  mean larger

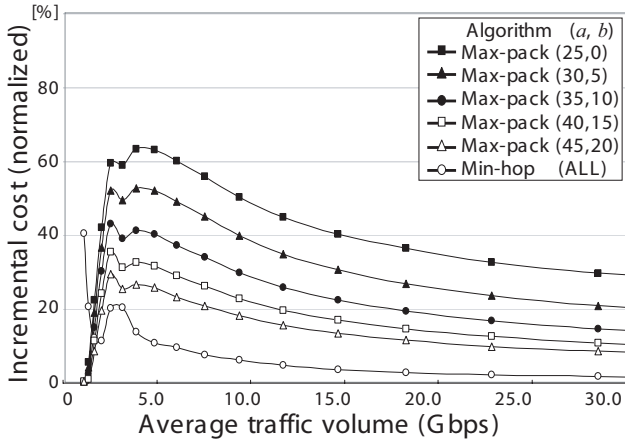


Fig. 6. Network cost with different contract/cancellation rates ( $a - b = 20\%$ ).

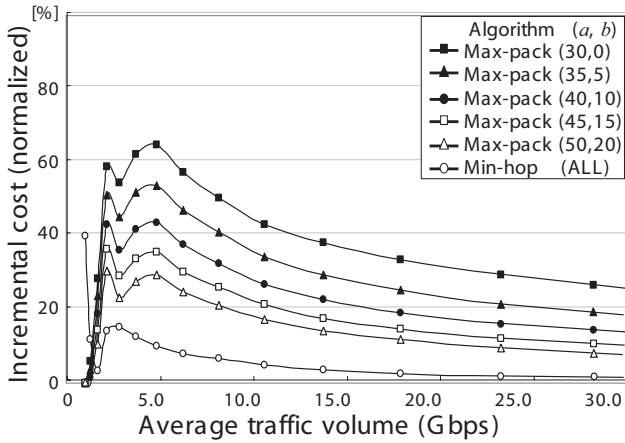


Fig. 7. Network cost variation in terms of *Age*.

numbers of incremental design steps are necessary to reach a certain average traffic volume. The behavior of the incremental cost depends on parameters  $a$  and  $b$  as shown in Fig. 5-7. For example, the maximum normalized incremental cost depends on  $a$  and  $b$  values. Further, even when  $a - b$  is constant, the incremental cost strongly depends on each parameter  $a$  and  $b$  for the Max-pack algorithm.

### B. Impact of Using Parameter *Age* to Represent Network Cost Variations

In Sec. II.B, we proposed and introduced a new parameter *Age*. Figure 8 is the re-plot of Fig. 5 for the Max-pack algorithm where the horizontal axis is redrawn using *Age*. We can split the figure into three distinctive domains; in Domain 1, the normalized incremental cost is, approximately, a quadratic function of *Age*. The normalized cost remains almost constant in Domain 2, and in Domain 3 it suddenly decreases and approaches zero. With exhaustive numerical experiments, we have verified that this tendency is shared by different pairs of parameters  $(a, b)$ . It was found that the shapes of the cost variations are mutually analogous and that maximum costs are proportional to  $Age^*$ . This implies that we can estimate the cost variations for the Max-pack algorithm from one  $(a, b)$  pair to another  $(a, b)$  pair without intensive calculations. Indeed, it

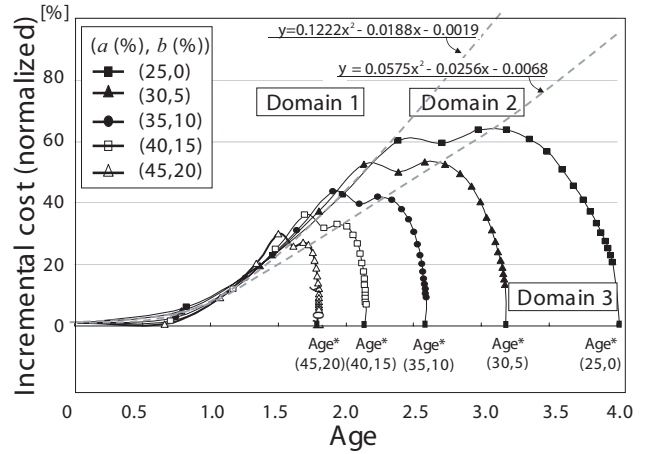


Fig. 8. Network cost with different contract/cancellation rates ( $a - b = 30\%$ ).

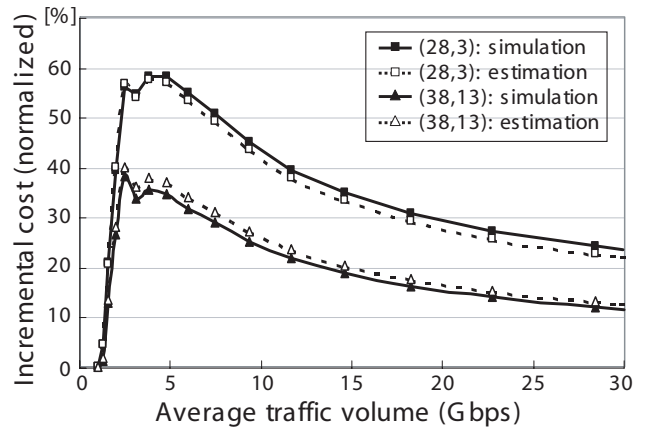


Fig. 9. Estimation of network cost using *Age*.

is proved in Fig. 9 that the network cost variations for (28, 3) and (38, 13) are well estimated by using only the one result for (25, 0). In Fig. 9, “(X, Y): estimation” is derived by using simulation results for (25, 0) shown in Fig. 8, and “(X, Y): simulation” is obtained by individual simulations. It is thus found that the *Age* parameter enables us to effectively estimate the network cost variations in quasi-dynamic network design.

### C. Network Design Considering Different Service Traffic Types

In the previous section, we designed a network that accommodates one specific service, in other words the service traffic is represented with one set of  $(a, b)$ . This assumption can be valid if there is a dominant service in terms of traffic demands, however, in the future broadband service environment, it may not be true and it is plausible that multiple kinds of service traffic with different service holding times may exist. In this section, we assume several traffics each of which has different service holding times defined by different probability distributions (Fig. 10). The distributions are defined so that they have common average values in terms of  $a$  and  $b$ , respectively, where the cancellation ratio  $b$  is automatically determined by  $a - b = 10\%$ . Comparisons of the assumed traffic distributions where the average of  $(a, b)$  is (30, 20) for

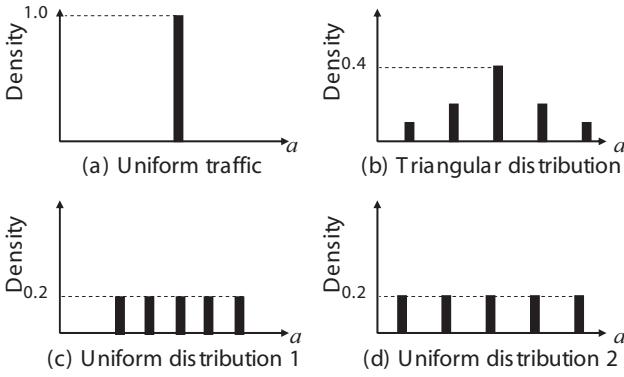


Fig. 10. Traffic distributions.

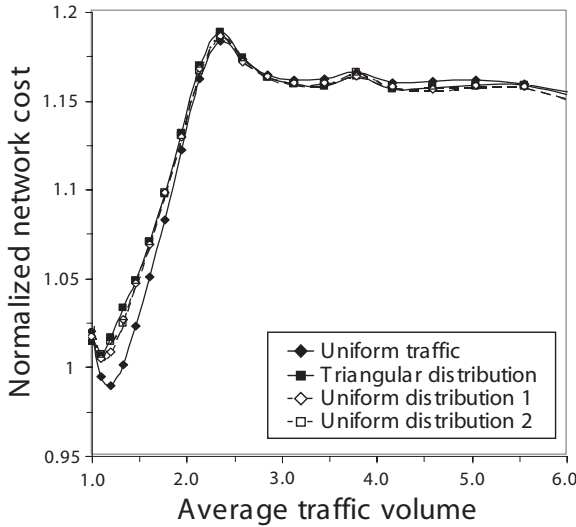


Fig. 11. Impact of the different traffic distributions on network cost variations.

each distribution are shown in Fig. 11. The results are almost same among different distributions shown in Fig. 10. This implies that the cost variation will be well predicted by using the average values of  $(a, b)$ , when different services each of which has different set of  $(a, b)$  value for a fixed  $a - b$  value.

Next, we discuss the effect of different  $a - b$  values, and propose a new network incremental design algorithm. Hereafter we classify services into two major categories of services in terms of the traffic distributions; services with long and short service holding times. Suppose that traffic  $T_L$  has long service holding time and  $T_S$  has short. These traffics are separated in electrical path layer, i.e. they are accommodated within different EPs, but EPs each of which accommodates different service traffic can be accommodated within the same OP(s). From the result of Sec. III.A, we can deduce that Min-hop algorithm is suitable for  $T_L$  and Max-pack algorithm has certain advantage for  $T_S$ . Therefore, we propose a combined method which, at each network redesign, first applies the Min-hop algorithm to accommodate  $T_S$  and then the Max-pack algorithm to accommodate  $T_L$ . The same procedure is applied in subsequent expansions.

Figures 12 and 13 show comparisons of the Max-pack, Min-hop, and Combined algorithms for the sum of two traffic flows,  $T_L$  and  $T_S$ , where different  $(a, b)$  values for  $T_S$  are

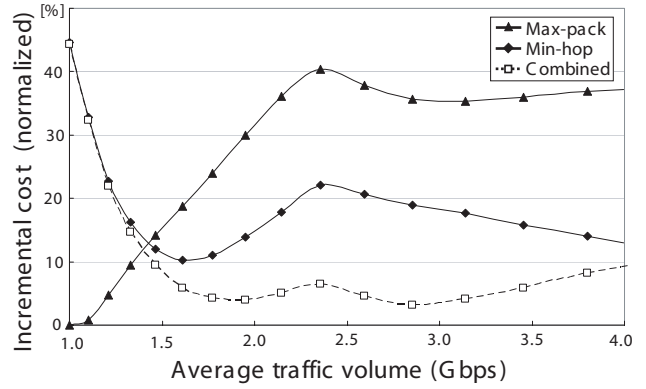


Fig. 12. Network cost for two different traffics flows ( $(a, b) = T_L : (10, 0), T_S : (30, 20)$ ).

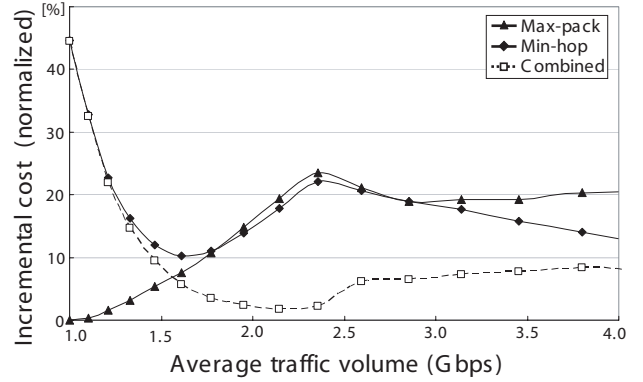


Fig. 13. Network cost for two different traffics ( $(a, b) = T_L : (10, 0), T_S : (50, 40)$ ).

used. The initial values of both  $T_L$  and  $T_S$  are set at 0.5 Gbps (so the total amount of initial traffic is 1.0 Gbps), and the service traffic parameter  $(a, b)$  of  $T_L$  is set at  $(10, 0)$ , while that of  $T_S$  is set at  $(30, 20)$  and  $(50, 40)$  in Fig. 12 and 13, respectively. This means that the traffic increment at each re-design is 10 % and the ratio of  $T_L$  and  $T_S$  is set to be constant. In comparison to Fig. 5-7, Fig. 12 and Fig. 13 more apparently show that the design step at which incremental costs of the Max-pack algorithm and the Min-hop algorithm cross becomes later when  $a - b$  becomes smaller. The results in Fig. 12 and Fig. 13 demonstrate that the service holding time of  $T_S$  has a substantial impact on the cost variation. In Fig 12, the costs obtained by Combined algorithm and Min-hop algorithm show the same value at the initial design step. This is because the total initial traffic of  $T_L$  and  $T_S$  is not large enough to fill most OPs (2.5Gbps). The Combined algorithm achieves smaller cost than the Min-hop algorithm after a certain number of incremental design steps. At the 9th design step, the gap between the two algorithms is about 10%. When compared to the Max-pack algorithm, the maximum gap is about 35%. In Fig. 13, a different service holding time is assigned to  $T_S$ , i.e. the average connection life is smaller. Around the 8th design step, the normalized cost increment becomes almost zero, that is to say, the ideal design is yielded by using the combined algorithm. It increases after that, but the incremental cost is smallest among the three designs.

The total hop counts of all EPs and average OPs usages at

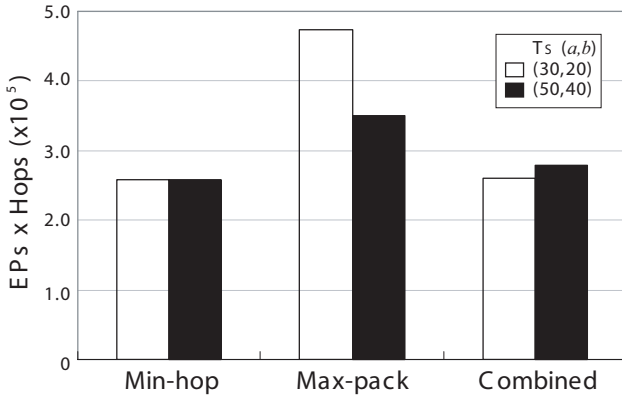


Fig. 14. Total number of EPs × Hops (10th design step).

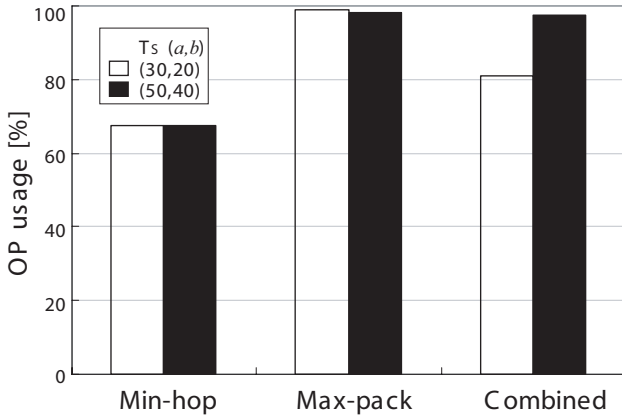


Fig. 15. Average usage of OPs (10th design step).

the 10th design step are given in Fig. 14 and 15, respectively. We can verify that the Min-hop algorithm provides shorter EPs at the expense of lower OP utilization. On the other hand, the Max-pack algorithm provides much higher OP usage, however, it increases EP lengths. As for the Combined algorithm, the total number of “EPs × Hops” approaches that of the Min-hop algorithm while the OP usage is much higher than that of the Min-hop algorithm. The results demonstrate that we can effectively develop quasi-dynamic network design algorithms to handle multiple services by applying different routing strategies (Max-pack and Min-hop algorithms) to each service depending on the service holding time.

#### IV. CONCLUSION

Detailed evaluations of the repetitive design of networks that can adapt to the expected continual network expansion have been described for the first time. We proposed quasi-dynamic network design algorithms that enable cost-effective expansion of multi-layered photonic networks. The evaluations provide us with some useful insights in that (1) the service parameter representing holding times has a crucial impact on the optimum design, (2) normalized incremental network costs attained using the Min-hop design approach zero (the cost approaches that obtained with zero-based ideal design) after a certain number of network redesigns and (3) the Max-pack algorithm should be selected if the estimated number of design steps is small (i.e., the envisioned network update frequency is

low during the network system life). Otherwise, the Min-hop algorithm provides good result. The new parameter of *Age* was then introduced; it effectively represents service holding time and incremental design interval. We showed that *Age* can well characterize the variation in the network cost for the Max-pack algorithm after repeated network redesign by identifying the domain and using an empirically obtained estimation formula. Furthermore, the effect of a change in the value of *a* (service contract rate) was discussed. It was demonstrated that the average value of *a* is critical; different distributions of the value *a* with the same average value give almost the same results in terms of network cost. It was thus shown to give a sophisticated way of estimating the cost variation against repetitive network designs considering different service holding times. In other words, the two dimensional parameter space (*a, b*) can be effectively reduced to the single parameter space, *a - b*, for cost evaluation, which significantly eases the computational burden (*b* is the rate of service cancellation). The network design algorithm was then extended so that it can be applied to a network where multiple service holding times need to be considered: the combined algorithm that reflects service traffic parameters was proposed. We have shown that lower network costs can be attained by taking advantage of merits of both the Min-hop and Max-pack algorithms. The discussion and results presented in this paper provide us with an organized perspective regarding quasi-dynamic network design for future broadband services.

#### APPENDIX

Network cost is the sum of costs of nodes and links. The costs for each node and link are given by the following equations. Specific cost values used for the calculations are up-dated versions of those given in [20].

##### Node cost

$$C_{\text{Node}} := \sum_{i=1}^N (C_{\text{NNI}} \times \text{NNI}_i + C_{\text{UNI}} \times \text{UNI}_i + C_{\text{OXC}} + C_{\text{POS}} \times \text{POS}_i + C_{\text{Router}} \times R_i + C_j \times R_i \times (R_i - 1))$$

##### Link cost

$$C_{\text{Link}} := \sum_{i=1}^N \sum_{j=1}^N \left\{ C_F \times D_{ij} \times W \times F_{ij} + C_{\text{Amp}} \times \frac{D_{ij}}{\text{dis}} \times F_{ij} \right\}$$

$C_{\text{NNI}}$ : OXC NNI (Network Node Interface) port cost per wavelength

$C_{\text{UNI}}$ : OXC UNI (User Network Interface) port cost per wavelength

$C_{\text{OXC}}$ : OXC base cost

$C_{\text{POS}}$ : OXC/Router interface cost (POS: Packet-Over-SONET/SDH basis)

$C_{\text{Router}}$ : EXC/Router cost

$C_j$ : EXC/Router junction cost (10 Gigabit Ethernet basis)

$C_F$ : Optical Fiber cost per km

$C_{\text{Amp}}$ : Amplifier cost

$\text{NNI}_i$ : Number of NNI ports at node *i*

$\text{UNI}_i$ : Number of UNI ports at node *i*

$\text{POS}_i$ : Number of POS ports at node *i*

- $R_i$ : Number of EXC/Router at node  $i$   
 $D_{ij}$ : Distance between nodes  $i$  and node  $j$   
 $W$ : Maximum number of wavelength per fiber  
 $F_{ij}$ : Number of fiber between node  $i$  and node  $j$   
 $dis$ : Amplifier span (km)

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**Koichi Kanie** received the B.E. degree in department of electrical and electronic engineering and information engineering from the Nagoya University, Nagoya, Japan, in 2005. He is now in a master course in the Department of Electrical Engineering and Computer Science. His research interests include photonic IP network design and evaluations.



**Hiroshi Hasegawa** received the B.E., M.E., and D.E. degrees all in Electrical and Electronic Engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 1995, 1997, and 2000, respectively. From 2000 to 2005, he was an assistant professor of the Department of Communications and Integrated Systems, Tokyo Institute of Technology. Currently he is an associate professor of Nagoya University. His current research interests include photonic networks, image processing (especially super-resolution), multidimensional digital signal processing and time-frequency analysis. He received the Young Researcher Awards from SITA (Society of Information Theory and its Applications) and IEICE (Institute of Electronics, Information and Communication Engineers) in 2003 and 2005, respectively. Dr. Hasegawa is a member of IEICE, SITA and IEEE.



**Ken-ichi Sato** (M'87-SM'95-F'99) received the B.S., M.S., and Ph.D. degrees in Electronics Engineering from the University of Tokyo, in 1976, 1978, and 1986, respectively. He is currently a professor at the Graduate School of Engineering, Nagoya University, and he is an NTT R&D Fellow. Before joining the university in April 2004, he was an executive manager of the Photonic Transport Network Laboratory at NTT. His R&D activities cover future transport network architectures, network design, OA&M (operation administration and maintenance) systems, photonic network systems including optical cross-connect/ADM and photonic IP routers, and optical transmission technologies. He has authored/co-authored more than 200 research publications in international journals and conferences. He holds 35 granted patents and more than 100 pending patents. He received the Young Engineer Award in 1984, the Excellent Paper Award in 1991, and the Achievement Award in 2000 from the Institute of Electronics, Information and Communication Engineers (IEICE) of JAPAN. He was also the recipient of the distinguished achievement Award of the Ministry of Education, Science and Culture in 2002. His contributions to asynchronous transfer mode (ATM) and optical network technology development extend to co-editing the *IEEE Journal on Selected Areas in Communications* (three special issues) and the *IEEE Journal on Lightwave Technology* (special issue), organizing several workshops and conference technical sessions, serving on numerous committees of international conferences including OFC and ECOC, authoring a book, *Advances in Transport Network Technologies* (Artech House, 1996), and co-authoring thirteen other books. He is a Fellow of the IEICE of Japan.