Coarse Granular Optical Routing Networks Utilizing Fine Granular Add/Drop

Yuki Taniguchi, Yoshiyuki Yamada, Hiroshi Hasegawa, and Ken-ichi Sato

Abstract—**We propose a novel network architecture that exploits coarse granular routing while add/drop operations are done at wavelength granularity. For the proposal, we introduce a node architecture and a network design algorithm. Numerical results demonstrate that the proposed architecture's performance approaches that of single layer optical path networks while substantially reducing hardware scale.**

Index Terms—**coarse granular routing; grouped path routing; optical path network; waveband selective switch.**

I. INTRODUCTION

The rapid increase in traffic volume is fueling the development of optical transport networks that utilize multi-degree ROADMs (Reconfigurable Optical Add/Drop Multiplexers). The present ROADM degree is limited to a small number, usually eight, however, further traffic expansion will occur in around 10-15 years because of the penetration of new broadband services such as IP TV, 8k/4k digital cinema and ultra-high definition TV [1]. This traffic increase will force larger scale ROADMs and optical cross-connects (OXCs). We thus have to develop optical networking technologies that can cost-effectively realize bandwidth abundant networks.

Hierarchical optical path networks that utilize waveband paths are being intensively investigated as a promising way to cope with the future traffic explosion [2-14]. Waveband paths are defined as bundles of multiple wavelength paths and used to route as many optical paths as possible at waveband granularity; wavelength granularity operations require more intensive hardware scale at each node and so should be minimized. The conventional hierarchical optical path nodes utilize the stacked switch architecture; waveband cross-connects (WBXCs) for routing waveband paths and wavelength cross-connects (WXCs) for adding/dropping and grooming of wavelength paths. The hardware scale reduction yielded by the introduction of wavebands can be significant with coarse granular routing when compared to single layer optical path networks, especially in the large traffic demand area. For example, switch scale reductions of 70-30 % for a WBXC that utilizes matrix switches [10] have been confirmed. When cross-connect systems that utilize 3-D MEMS based WSS/WBSS (Wavelength/WaveBand Selective Switch) are considered, the required number of MEMS (Micro Electro Mechanical Systems) mirrors can be greatly reduced, say, to 48% [11]. Hierarchical optical path networks groom wavelength paths, which includes terminating and unbundling waveband paths at intermediate nodes, to improve the utilization ratio of waveband paths and fibers. Efficient heuristic algorithms that incorporate effective grooming have been developed and shown to successively reduce port count and fiber number [12,13].

Recently, to reduce HOXC (Hierarchical Optical Cross-Connect) switch scale, a new HOXC architecture that separates the waveband add/drop function from WBXC has been proposed [11, 14]. This architecture can reduce WXC part switch scale more than the conventional HOXC architectures since wavelength paths to be added/dropped from/to electric layer don't need to go through the WXC part (WBXC either), while the conventional HOXC terminates waveband paths and then adds/drops wavelength paths in the WXC part.

The wavelength path grooming ratio is an important parameter that determines the total switch scale of a hierarchical optical cross-connect since WXC parts dominate the switch scale. The authors of [14] developed an efficient network design algorithm that incorporates a grooming ratio restriction. Their analyses showed that even when grooming ratio is restricted to a small value, say 0.25, the resultant network cost increase is marginal compared to the case where no restrictions are imposed. In other words, coarse granular routing (waveband routing) with supplemental intermediate grooming can create cost-effective networks and this tendency strengthens as traffic increases. However, the WXC part is still relatively large since some WSSs or large scale matrix switches are needed. It is thus attractive to realize high fiber utilization without using the WXC part.

Based on the investigations done so far, we propose here a novel network architecture that can reduce optical switch scale and enhance fiber utilization; we introduce its node architecture and network design algorithm. The proposed

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network exploits coarse granular optical routing; add/drop operations are performed at the wavelength granularity level. All wavelength paths in each fiber are grouped into some groups, and the node routes wavelength paths on the groups, i.e. in coarse granularity. The routing nodes offer no wavelength path level granularity cross-connect function, unlike the hierarchical optical path cross-connect, and hence wavelength grooming is not possible. The node architecture sets a 1x2 WSS for each connected input/output fiber to terminate/originate optical paths at each node, which makes it possible to add/drop any wavelength path at an arbitrary node. We call this routing scheme grouped routing, and call the bundle of wavelength paths used for coarse granular routing the grouped routing entity (GRE). We demonstrate in this paper that our approach yields a simple node architecture that will be effective in creating high throughput nodes cost effectively. We also develop a heuristic network design algorithm that packs as many wavelength paths as possible into GRE and as a result minimizes necessary fibers in the network. Numerical experiments show that the proposed network architecture greatly reduces the node cost while keeping the increase in fiber number over the equivalent single layer optical path network to an insignificant level. A preliminary version of our work on grouped routing was published at an international conference [15].

This paper is organized as follows. Section II detail of grouped routing network is described. In section III, we discuss the node architecture that realizes grouped routing. In section IV, we introduce the network design algorithm that performs grouped routing effectively. In section V, the results of numerical experiments are presented.

II. GROUPED OPTICAL PATH ROUTING

In this paper, we introduce a novel network architecture that utilizes coarse granular routing and fine granular add/drop operation. We call such networks grouped routing networks. The node architecture for grouped routing network is shown in Fig.1 (GR-OXCs). The wavelength set $\{\lambda_0, \lambda_1, \dots, \lambda_{MN-1}\}$is equally divided into several subgroups $G_i = \{\lambda_i, \lambda_{i+M}, \dots, \lambda_{i+M(N-1)}\}(i = 0,1, \dots, N-1)$ named grouped routing entities (GREs). M is the maximum number of lambdas accommodated in a subgroup, and N is the number of subgroups accommodated in a fiber. Hereafter we assume that F fibers are connected to the node respectively for the input and output sides. Express paths at a node are routed at GRE granularity, which simplifies the OXC nodes. Each GRE G_i is labeled by a positive integer i and the label is called GRE index. We call this OXC for GRE routing GR-OXC, whose structure is equivalent to WBXC (waveband cross-connect). On the other hand, any wavelength path in a GRE can be added/dropped from/to electric layer at any node traversed by the GRE. This operation is realized by 1x2 WSS equipped for each output/input fiber to select wavelengths (1x2 WSS at the output fibers can be replaced with 1x2 optical couplers).

Grouped routing corresponds to the situation where multiple nodes are concatenated by virtual pipes whose bandwidth equals to the capacity of GRE. We refer these virtual pipes as GRE pipes (Fig. 2). GRE pipes differ from usual waveband paths in conventional hierarchical optical path networks in that GRE pipes do not offer path functions such as termination as defined by ITU-T Rec. G.783 for digital paths [16]. A GRE pipe can even form a closed loop as shown in Fig. 3. A GRE pipe can be regarded as a virtual fiber; if a certain amount of service traffic exist between nodes, virtual fibers can be installed in a mesh like fashion, and when the service traffic between nodes is not enough to fill a virtual fiber capacity, a virtual fiber ring network will be created. This is similar to the present conventional optical networks that utilize mesh and ring fiber topologies.

In conventional hierarchical optical path networks, wavelength paths are always carried by a set of concatenated waveband paths and terminations of waveband paths are necessary for grooming and add/drop operations (Fig. 4). The drawback of this architecture is that the WXCs are still large since they route paths in the wavelength granularity. If direct waveband paths are established in an end-to-end manner, the WXCs are utilized only for add/drop and while node scale can be greatly reduced, fiber utilization tends to be poor which increases total network cost [13].

The combination of coarse granular routing and fine granular add/drop possible in grouped routing networks enables us to route wavelength paths whose source and destination node pairs are different via a GRE pipe. This makes the network architecture efficient even though WXCs are omitted. On the other hand, no wavelength path can traverse multiple GRE pipes. Thus the establishment of optimal GRE pipes is crucial. We will propose a suitable design algorithm in Sec. IV. GR-OXC implementation is explained in the next section.

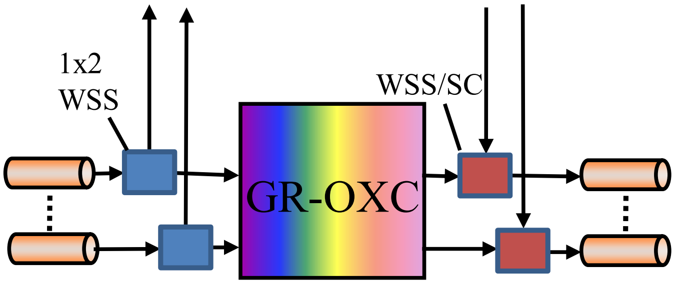

Fig. 1. Proposed node architecture for grouped routing (GR-OXC).

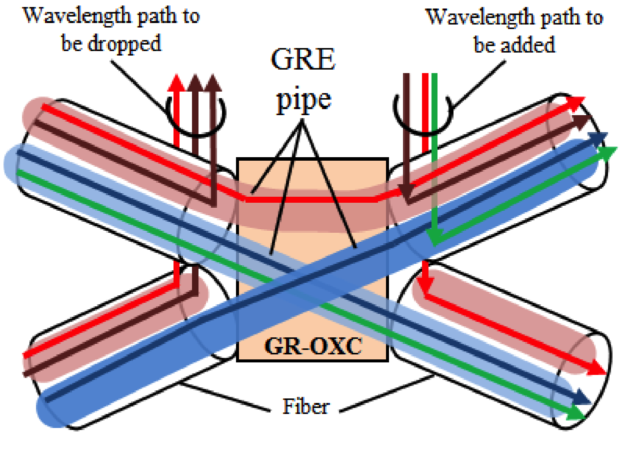

Fig. 2. Routing of GRE pipes at GR-OXC.

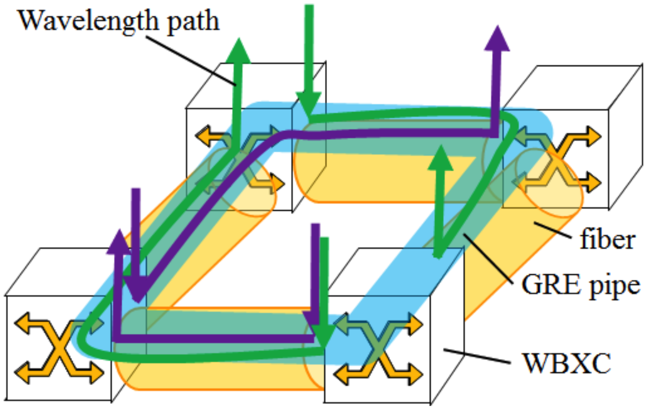

Fig. 3. GRE pipe forming closed loop.

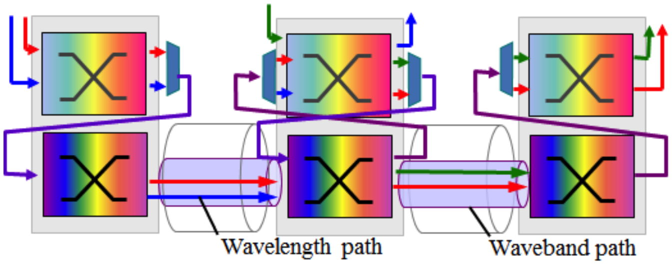

Fig. 4. Grooming and add/drop operation in hierarchical optical path networks.

III. IMPLEMENTATION OF GROUPED OPTICAL PATH ROUTING

Figures 5 and 6 show different implementations of the nodes in Fig. 1 where the GR-OXC parts are respectively realized by using matrix switches [17] and waveband selective switches [18]. These architectures are exactly the same in terms of logical routing capability and we hereafter call them GR-OXCs. The key devices are waveband MUX/DEMUXs (Multiplexer/Demultiplexer) [19] for Fig. 5 and WBSS [18, 20] for Fig. 6, which have already been developed and utilized in hierarchical optical path networks. We recently demonstrated a prototype of an ultra-compact WBSS monolithically integrated on a PLC (Planar Lightwave Circuit) chip. Figure 7 shows a 1x10 WBSS fabricated on a 82x53 mm^2 PLC chip [20]. This chip has no mechanical moving parts and thus is highly reliable.

The add/drop parts are separated from the GRE routing part. At the drop part, the wavelength paths dropped from the 1x2 WSSs are terminated and delivered to the electrical layer system. We may add matrix switches or transponder aggregator parts [21] to realize colorless/directionless/contentionless (C/D/C) add/drop capabilities. This C/D/C drop capability can also be realized with recently proposed ultra-compact multi-stage tunable filters [22], which have also been monolithically realized on PLC chips [22]. The C/D/C add part is much simpler. Output signals from transponders are routed to the desired fibers by small 1xF switches and then combined with the GR-OXC outputs by optical couplers. The optical couplers may be replaced by 1x2 WSSs to reduce the coupler loss. The realization of C/D/C add/drop parts is common to conventional single layer OXC nodes and lies outside the scope of this paper; we focus on switch scale in the routing part hereafter.

To use the GR-OXC switch in a matrix switch based node (Fig. 5), we need N FxF matrix switches with total port count of $2NF$. For the GR-OXC switch using WBSSs (Fig. 6), the switch scale is evaluated by the number of selective switches used. We assume one kind of fixed degree waveband selective switch; if the node degree is larger than that of the fixed waveband selective switch degree, multiple selective switches are used as shown in Fig. 8. Here, multiple selective switches are connected to an optical coupler (Fig.8) or simply concatenated. We assume the former configuration in this paper.

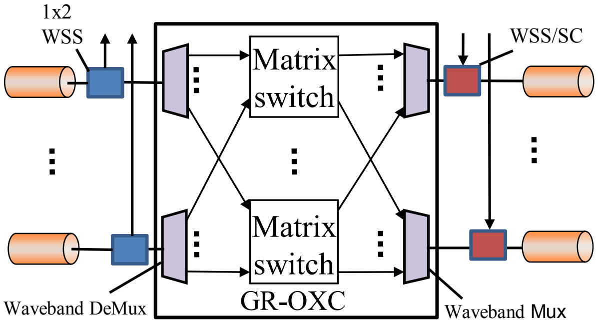

Fig. 5. A GR-OXC using matrix switches.

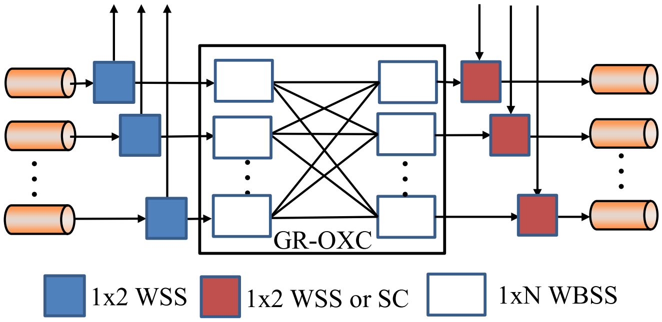

Fig. 6. A GR-OXC using WBSSs.

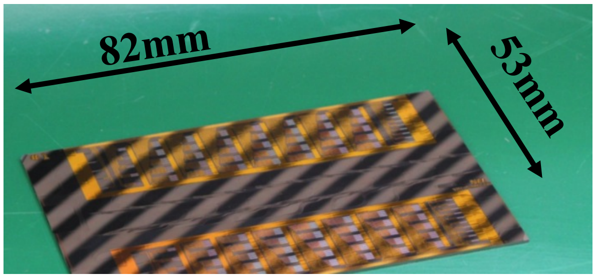

Fig. 7. A monolithic 1x10 WBSS chip [16].

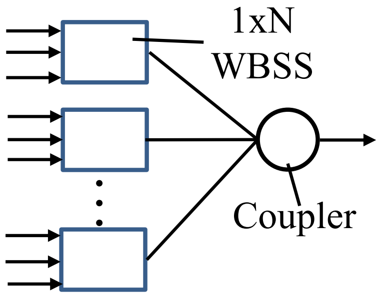

Fig. 8. Large degree WBSS construction.

IV. NETWORK DESIGN ALGORITHM FOR GROUPED OPTICAL PATH ROUTING

In this section, we propose a static network design algorithm for grouped routing optical path networks. We note that another important design issue is the dynamic network control scenario in which the blocking probability for dynamic traffic demand is minimized. Both static network design and dynamic network control scenario are used to evaluate the effectiveness of network architectures. The authors have already verified the effectiveness of the grouped optical path routing network architecture for a dynamic network control scenario in [24] where PCE (path computation element) and GMPLS (generalized multi-protocol label switching) are utilized; this issue is beyond the scope of this paper.

The general objective of static photonic network design is to minimize the given cost function, total link cost and total node cost, where optical path routes and wavelengths are determined so as to carry the given traffic demand. Even for the conventional single-layer optical path network, finding the optimal assignment that minimizes the cost function is computationally hard, i.e. NP-complete, due to so called the wavelength continuity constraint [23]. For grouped routing optical path network design, we must also find the optimal locations and GRE-index assignments for GRE pipes in addition to the accommodation of wavelength paths to GRE pipes. These additional tasks make it much more difficult to design grouped routing networks than conventional single-layer optical path networks. Unlike the ILP formulation for single-layer optical path network design, the routing and wavelength assignment of wavelength paths will be done on a graph where the nodes are carried over from the original topology and the links are changed by the establishment of GRE pipes. The envisaged application area of grouped optical path routing covers the heavy traffic demand area, and so we were unable to apply an ILP formulation to derive the optimal solution. Considering the complexity of the design problem, we propose a design algorithm that is based on the greedy and sequential accommodation of wavelength paths and the assignment routes and indexes to GRE pipes.

The most efficient accommodation of wavelength paths into GRE pipes occurs when each GRE pipe is fulfilled with wavelength paths connecting the end points of that GRE pipe. Thus the algorithm firstly searches for sets of wavelength paths where each set consists of wavelength paths whose source and destination nodes are same and the number of wavelength paths in the set is multiple of the GRE pipe's capacity (in Step1). For routing of such GRE pipes, no restriction is imposed except for the end points. In other words, we can relocate these paths to improve fiber utilization or to eliminate fibers that are not well utilized. Thus these GRE pipes are marked as “reserved” until the other GRE pipes are established. After finishing this procedure, the residual wavelength path demands are sparsely distributed in the network. Our algorithm searches for the route candidates for paths whose source and destination node pairs are most distant among remaining wavelength path demands, and finds the other wavelength paths whose source and destination nodes are along each route candidate to be accommodated so that the new GRE pipe can be sufficiently fulfilled (in Step2-1). The algorithm follows to the routing and index assignment of the GRE pipe so that the fiber cost increment is minimized and the GRE pipe traverses all the source and destination nodes of wavelength demands (in Step2-2) carried by the GRE pipe. Thus in Step3, the routes and indices of the reserved GRE pipes are determined. After all wavelength paths are accommodated, the algorithm searches for not sufficiently utilized fibers and tries to remove them by relocating GRE pipes that traverse the fibers (in Step4). The detailed procedures are as follows.

<Proposed network design algorithm>

Step 0. Parameter definition

Assume that the given network topology is expressed as an equivalent bidirectional graph $G = (V, A)$ where V is the set of all nodes and A is the set of all links. Let $\mathrm{dem}(n_s, n_d)$ be the number of wavelength from n_s to n_d ($n_s, n_d \in V, n_s \neq n_d$) and M be the number of wavelength paths that can be accommodated in a GRE pipe.

Step1. Search for wavelength path sets carried by direct GRE pipes

For each node pair (n_s, n_d), reserve $\left\lfloor \frac{\mathrm{dem}(n_s,n_d)}{M} \right\rfloor$ GRE pipes between the nodes. Assign $M\left\lfloor \frac{\mathrm{dem}(n_s,n_d)}{M} \right\rfloor$ wavelength paths to these GRE pipes and

$$\mathrm{dem}(n_s, n_d) = \mathrm{dem}(n_s, n_d) - M\left\lfloor \frac{\mathrm{dem}(n_s, n_d)}{M} \right\rfloor.$$

Step2. Accommodation of remaining wavelength paths

Step2-1. Search for route candidates and set of wavelength paths that can be accommodated in GRE pipe

In descending order of shortest hop counts, apply the K-shortest-path algorithm to find route candidates $Route_l$ $(1 \leq l \leq K)$ for wavelength demands in $\mathrm{dem}(n_s, n_d)$. For each $Route_l$, find a set of wavelength demands such that they are accommodated in a GRE pipe on $Route_l$ so as to maximize the utilization ratio of the pipe.

Step2-2. Route and index assignment of GRE pipes

Select the route candidate among the set $\{Route_l\}$ whose fiber increment is the smallest, and establish a GRE pipe on it and accommodate the corresponding wavelength demands. The procedure can be implemented as the following processes: define graphs G_i^{GRE} $(0 \leq i \leq N-1)$ for the i th GRE index where G_i^{GRE} is equivalent to the original G except for the link weight (see Fig. 9) where the weight for link (n_s, n_d) on G_i^{GRE} is defined by

$$W_i(n_s, n_d) = \begin{cases} \dfrac{C_F(n_s, n_d)}{N} & \text{if b th GRE is not used in some fiber on the } (n_s, n_d) \\ (1+\Delta)\dfrac{C_F(n_s, n_d)}{N} & \text{otherwise} \end{cases}$$

with $\Delta \ll 1$ for encouragement of the use of existing fibers as much as possible and the cost $C_F(n_s, n_d)$ of a fiber between (n_s, n_d). On each $Route_l$ $(1 \leq l \leq \mathrm{K})$, find the index i with the smallest weight on $Route_l$ for each graph $G_i^{GRE}(\mathrm{i} = 0,1,\ldots,\mathrm{N}-1)$. Select $Route_l$ for which the GRE pipe offers the minimum fiber increment. Establish a pipe on $Route_l$ and assign the wavelength paths found in Step2-1 to the GRE pipe; if there are multiple routes with the same fiber increment, select the route with the highest utilization ratio among the routes. Repeat Step2 until all wavelength path demands are accommodated.

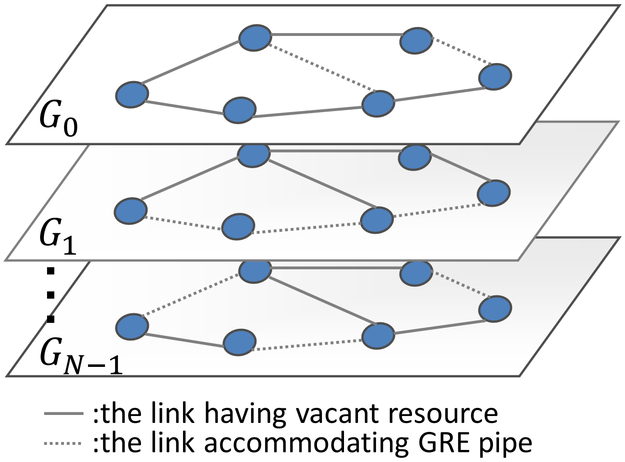

Fig. 9. A multi-layered graph represents free capacity of GRE

Step3. Establishment of reserved GRE pipes

For GRE pipes reserved in Step1, in descending order of shortest hops, select the pair of route and GRE index that achieves minimum weight among all route candidates and all layers $G_i^{GRE}(\mathrm{i} = 0,1,\ldots,\mathrm{N}-1)$. If multiple routes are found, select one randomly. Establish a GRE pipe on the selected route and GRE index. Repeat Step3 until all GRE pipes are accommodated.

Step4. Rerouting of GRE pipes

Let W be a threshold of fiber utilization ratio, and $U(F_a)$be utilization ratio of fiber F_a. Define C_{before} as the cost needed for F_a and GRE pipes accommodated in F_a satisfying

$$C_{before} := C_{F_a} + \sum_{i=0}^{N-1} 2C_{B\_NNI} \times \mathrm{hop}_{GRE_{F_a}^i}$$

where C_{F_a}, C_{B_NNI} is the cost of F_a, NNI (Network-Network Interface) port of GR-OXC, and $\mathrm{h}op_{GRE_{F_a}^i}$ stands for the number of hops of the GRE pipe accommodated in F_a and that has i th GRE index. For each F_a, remove all wavelength paths that go through F_a if $U(F_a)$ is smaller than W. Then, reestablish GRE pipes in the network without the fiber so that all removed wavelength paths can be accommodated without increasing the fiber number. Define C_{after} as the cost needed for reestablishment of GRE pipes satisfying

$$C_{after} := \sum_{p=1}^{P} 2C_{B\_NNI} \times \mathrm{hop}_{GRE_p}$$

where P is the number of reestablished GRE pipes and $\mathrm{h}op_{GRE_p}$stands for the number of hops of the p th GRE pipe. If reestablishing GRE pipes is not possible without increasing the fiber number or failing to satisfy

$$C_{after} < C_{before}$$

cancel fiber removal. Repeat Step4 until all fibers are checked.

V. NUMERICAL EXPERIMENTS

The performance of the proposed algorithm is analyzed by comparing it with the single layer optical path network in terms of the numbers of necessary fibers, optical switch ports, and selective switches. We implemented the proposed algorithm and simulated network design under a given demand.

The proposed algorithm employs the following design parameters; the route candidates used in Step2-1 of proposed algorithm are all possible shortest routes between node pairs for the regular mesh networks. In the non-regular mesh networks, the route candidates are considered up to 5. The threshold of fiber utilization, W, used in Step4 is set at 50%, and the maximum number of hops allowed for the rerouting route found in Step4 is set equal to or less than the minimum hop number between the node pair plus 2, or in other words, approved hop-slug is 2. The proposed node architecture has no wavelength converter, and the WBSS-based WBXC uses 1x10 WBSSs; the comparison assumes a single layer OXC using 1x10 WSSs. The capacity of fiber is set at 80 wavelengths. Randomly distributed traffic demands are assumed and they are represented as the average number of wavelength paths between each node pair. Average number of wavelength paths between each node pair ranges from 5 to 20 considering the envisaged large traffic volume, which is the target of the proposed network architecture. The evaluated cost is the average of 20 trials with different traffic distributions; normalization is against the cost of the single layer equivalent.

A. Analysis of GRE Capacity

In grouped optical path routing, GRE capacity, M, is a key parameter determining network cost. We evaluated 4 values (M=4, 8, 10, and 16) on a 7x7 regular mesh network. Figures 10, 11 and 12 show normalized number of fibers, optical cross-connect ports and selective switches, respectively. Small M gives better fiber utilization and hence yields smaller fiber cost. For example, Fig. 10 indicates that the increment in the number of fibers with M=4 is very small compared with the single layer optical path network. On the other hand, large M gives better cross-connect port cost reduction since the available reduction rate in port counts is higher than that with small M (see Fig. 11). Additionally, gaps among the GRE capacities in both normalized number of fibers and selective switches gradually reduce as wavelength path demand increases as shown Fig. 10 and Fig. 12. Please note that, in most networks (except for long haul networks), node cost is the major CAPEX (CApital EXpenditure) portion of total network cost; fiber cost is relatively small. WBSS is expected to be cost effective and its footprint is much smaller than the WSS of same capacity (same switch degree). Please note that a one chip integrated WBSS has already been fabricated, see Fig. 7. The number of switch elements in a WBSS depends on GRE capacity *M*, and a large *M* needs fewer switches. Reducing *M* does not reduce WBSS size by the same amount. As a result, considering the trade-offs among size of WBSSs, number of fibers, and number of ports, the most appropriate GRE capacity, *M*, will be around 10 for the tested traffic demand intensities.

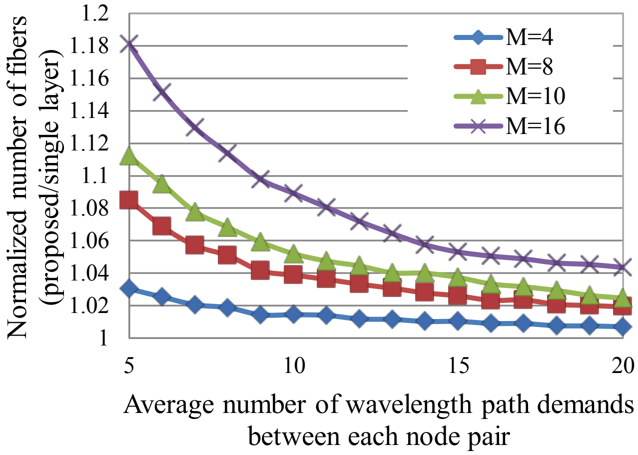

Fig. 10. Normalized number of fibers with different GRE capacity.

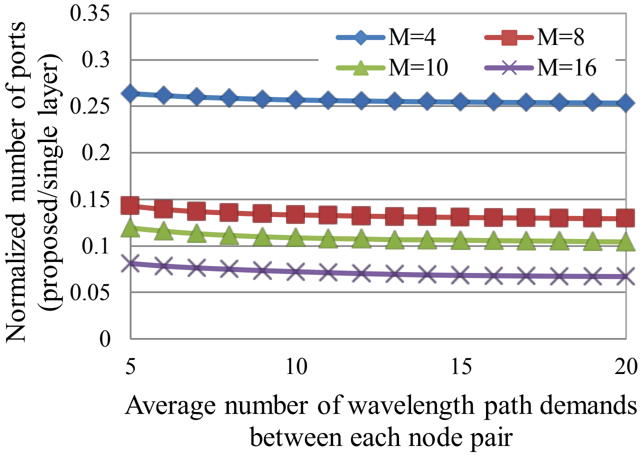

Fig. 11. Normalized number of ports with different GRE capacity.

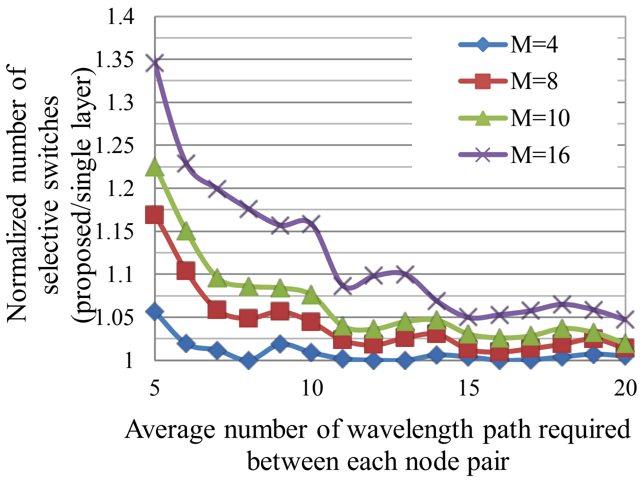

Fig. 12. Normalized number of selective switches with different GRE capacity.

B. *Dependency on Topologies*

The impact of grouped routing on various topologies with different network scale and configuration is analyzed in this subsection.

Regular mesh networks

We tested NxN regular mesh networks (N = 5,6,7,8). The GRE capacity is set at 10. Figures 13, 14 and 15 plot normalized number of fibers, cross-connect port counts and selective switches, respectively. Figure 13 shows that the proposed network requires slightly more fibers in the small traffic demand area, however, the increment decreases as the demand becomes large and reaches 5% for wavelength path demands larger than 15 for all regular mesh networks tested. By contrast, Fig. 14 demonstrates the significant reduction in cross-connect port count possible; it approaches 90% as traffic increases. In both graphs, larger topologies can gain greater cost reductions. The reason is that the number of wavelength paths that can be accommodated in the GRE pipes increases as the pipes go through more intermediate nodes. Figure 15 shows that the proposed network suppresses the increase in selective switch number to no more than 6% with wavelength path demand of 20. Since both WSS and WBSS are assumed to have degree of 1x10, the number of selective switches at a node increases whenever the number of incoming fibers exceeds a multiple of 10. Therefore, the normalized number of selective switches can jump as traffic demand increases. In smaller topologies, the bumps become enhanced because the entire number of selective switches is small; as wavelength path demand increases, the fluctuation decreases. The variations of results among 20 trials range lie in a relatively small region around their averages; for example, the ranges are [0.98, 1.02] and [0.98, 1.04] for 5x5 and COST266 networks, respectively, when the average number of wavelength paths between each node pair is 15. The results shown in these graphs confirm that the proposed architecture can greatly reduce node cost and effectively suppress fiber cost increase in regular mesh networks.

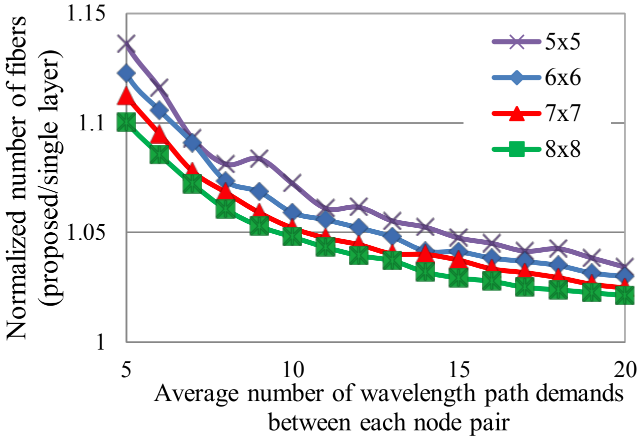

Fig. 13. Normalized number of fibers for regular mesh networks.

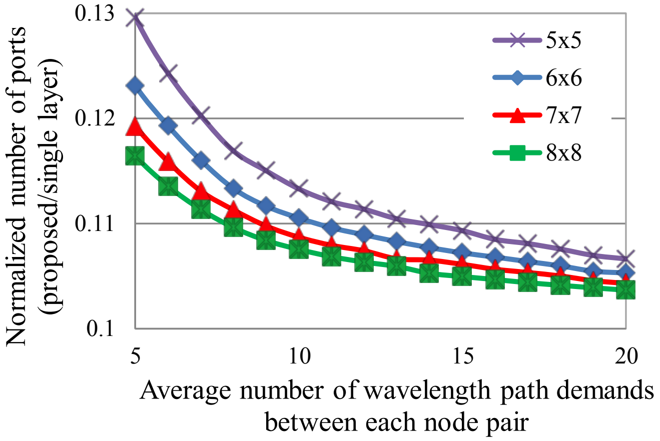

Fig. 14. Normalized number of ports for regular mesh networks.

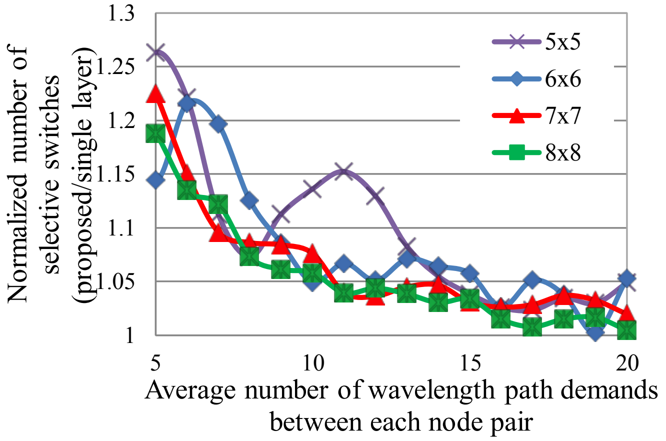

Fig. 15. Normalized number of selective switches for regular mesh networks.

Real topologies

We employed COST266 pan-European network (26-nodes, 51-links, Fig. 16) [25], USNET (24-nodes, 42-links, Fig. 17) [26] and Phoenix network (31-nodes, 49-links, Fig. 18) topologies [27]. The GRE capacity is set at 8. Figures 19, 20 and 21 show normalized number of fibers, cross-connect port counts, and selective switches, respectively. For these topologies, the increments are slightly increased compared to the regular mesh networks since there are fewer GRE route candidates and hence optimization in terms of GRE routing and wavelength accommodation tends to be weaker. However, the proposed network suppresses the increase in fiber and selective switch number to no more than 4% and 10%, respectively, with wavelength path demand of 20. Moreover, they reduce the port number by over 89%. Thus it is noted that proposed network is effective even with real topologies. The Phoenix network topology yields the best cost reduction among these topologies since it has the most nodes. The difference between COST266 and USNET is marginal since they have almost the same number of nodes.

Fig. 16. COST266 pan-European network topology.

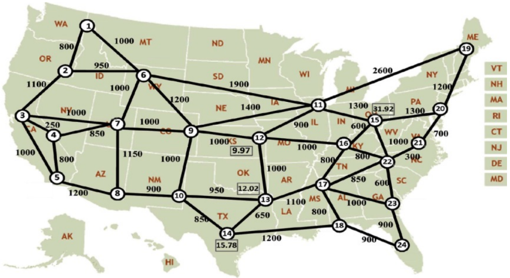

Fig. 17. USNET topology.

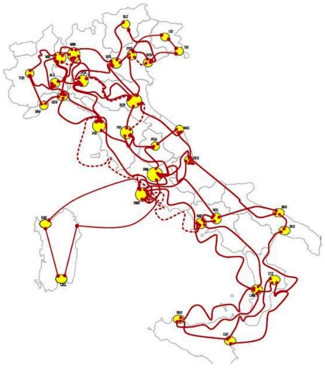

Fig. 18. Phoenix network topology.

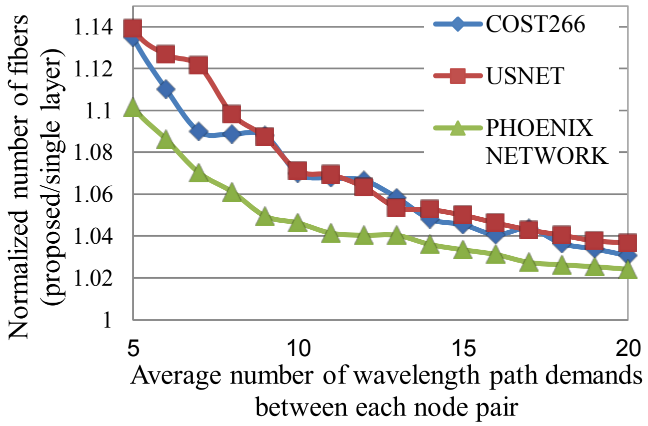

Fig. 19. Normalized number of fibers for real topologies.

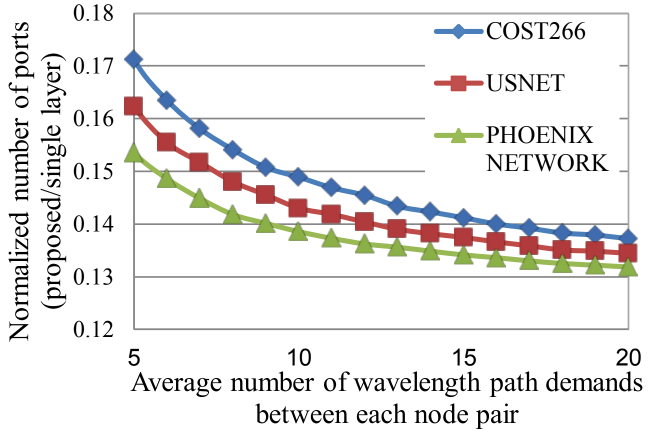

Fig. 20. Normalized number of ports for real topologies.

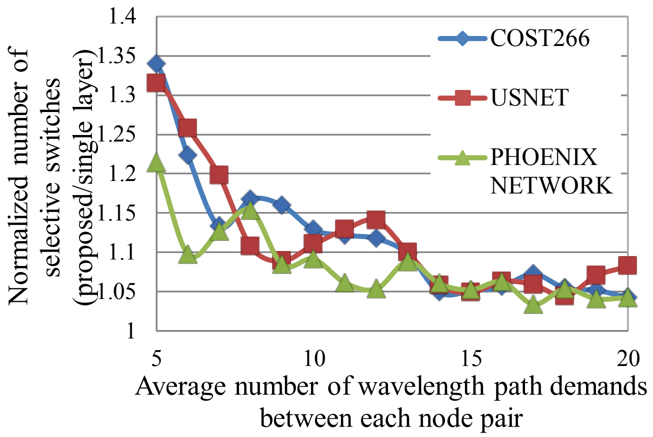

Fig. 21. Normalized number of selective switches for real topologies.

C. Analysis on Required Number of WBSSs

We evaluated the distribution of the number of WBSSs for each node using the following parameters.

- Physical network topology: 5x5 regular mesh network.
- Average number of wavelength path demands between each node pair: 20.
- Capacity of GRE: 10 wavelengths per GRE, i.e., 8 GREs per fiber.
- WBSS degree: 1x20 WBSS.

Figure 22 shows the distribution of the required number of WBSSs for each node. Central nodes in the topology need more WBSSs than the outer nodes since most GRE pipes tend to go through the central nodes.

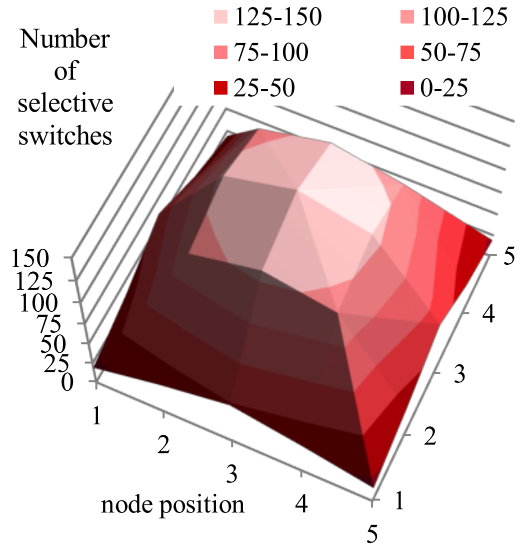

Fig. 22. Distribution of WBSSs in 5x5 network.

VI. CONCLUSIONS

In this paper, we proposed a new network architecture that introduces GRE and wavelength level add/drop operations at each node. The node architectures were also introduced. We also developed an efficient static network design algorithm for the proposed network. Numerical experiments demonstrated that the proposed network suppresses the increase in the number of fibers and selective switches over the single layer optical path network to an insignificant level, while substantially reducing the number of optical switch ports and footprint.

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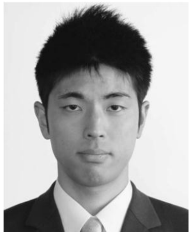

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