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PAPER

Impact of Elastic Optical Paths That Adopt Distance Adaptive Modulation to Create Efficient Networks

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SUMMARY We propose optical path routing and frequency slot assignment algorithms that can make the best use of elastic optical paths and the capabilities of distance adaptive modulation. Due to the computational difficulty of the assignment problem, we develop algorithms for 1+1 dedicated/1:1 shared protected ring networks and unprotected mesh networks to that fully utilize the characteristics of the topologies. Numerical experiments elucidate that the introduction of path elasticity and distance adaptive modulation significantly reduce the occupied bandwidth.

key words: *elastic optical path network, distance adaptive modulation, routing and spectrum assignment, network design*

1. Introduction

Due to the rapid penetration of broadband access including Asymmetric Digital Subscriber Line (ADSL) and Fiber-to-the-home (FTTH), the amount of backbone network traffic has been continuously increasing. This large increase in traffic demand has driven the introduction of wavelength routing optical path networks that utilize reconfigurable optical add/drop multiplexers (ROADMs). New broadband services that include 4k/8k ultra-high definition video distribution, the original bitrate of which is 6 Gbps/72 Gbps, and e-science are beginning to emerge and hence the amount of backbone network traffic is expected to explode in the near future. In order to handle the traffic explosion, maximizing the frequency utilization efficiency of optical fibers is critical to realize cost-effective large scale networks.

The recently proposed spectrum-sliced elastic optical path network (SLICE) can attain greatly enhanced spectral resource utilization by introducing the finer frequency granularity called frequency slot [1]. This enables a different number of continuous frequency slots to be allocated to match each transmission requirement set by desired bitrate and transmission distance. SLICE can minimize the total required number of frequency slots, which makes SLICE more efficient than the conventional ITU-T (ITU-T: International Telecommunication Union Standardization Sector) grid-based carrier frequency assignment method. To fully utilize the SLICE capability, two key technologies have been developed; rate-flexible transponders based on, for example, Orthogonal Frequency Division Multiplexing (OFDM) [2] or Nyquist wavelength division multiplexing (WDM) and bandwidth-flexible wavelength cross-connects. More recently, an adaptive modulation technique has been developed that enhances transponder flexibility in terms of bitrate adaptive [3]–[15] and distance adaptive [16]–[21]. With bit rate adaptive frequency slot allocation, the number of frequency slots assigned is tailored to the service bit rate. In distance adaptive modulation, the maximum number of bits per symbol is selected for each path, subject to the given transmission conditions such as transmission distance and node hop count. This is done by selecting an appropriate modulation format such as 16-QAM for short path lengths and QPSK for long path lengths [21]. If we can utilize universal transponders [22], all modulation formats can be realized without using different modulators, each of which implements a specific modulation format, and the distance adaptive scheme can realize its full cost efficiency. Regarding network design issues, investigations have been conducted on static SLICE network design algorithms with bitrate adaptive [3]–[11] and distance adaptive [16], [17] schemes, and dynamic SLICE network control algorithms with bitrate adaptive [12]–[15] and distance adaptive [18]–[20] schemes.

In this paper, we focus on the static SLICE network design algorithm that adopts distance adaptive modulation in various network topologies. The objective of this work is to create a network from scratch so as to minimize the total amount of resources such as fibers and node hardware used to satisfy a given path connection demand. The essential difficulty of static design in SLICE networks with distance adaptive modulation is that the number of slots necessary is not uniform for routes connecting the same source/destination nodes. Although the conventional approach is to utilize a simple design algorithm based on a path-by-path sequential heuristic, we need to develop a design algorithm that can simultaneously optimize the route assignment of all paths since route length determines the number of occupied slots. We start by newly proposing two routing and frequency slot assignment algorithms for 1+1 dedicated and 1:1 shared protected 2-fiber bidirectional ring networks. Both algorithms utilize the regular architecture of ring networks and minimize the necessary bandwidth in

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fibers while retaining maximum commonality with existing systems. Ring architectures are the commonly utilized configuration in metro networks worldwide. Next, we propose routing and frequency slot assignment algorithms for mesh networks. Due to the complexity of minimizing resource utilization, we propose an algorithm that assigns routes and frequency slots sequentially where routing is based on novel multi-stage integer linear programming (ILP) optimization. Through numerical experiments on both ring and mesh networks, we verify that our proposed methods for ring networks can reduce the necessary bandwidth by 43%/33% in 1+1 dedicated/1:1 shared protected ring networks compared to conventional ITU-T grid based networks. With regard to mesh networks, a SLICE network designed with proposed algorithm is substantially more efficient in various mesh network topologies especially in large demand area. The networks can accommodate up to 50% or more traffic than conventional ITU-T grid based networks. A preliminary version of this work has been presented at an international conference [16].

2. Preliminaries

In this paper, we focus on the static network design problem, where a set of path connection demands is given first and then the total amount of resources needed to accommodate the demands is minimized. Each path connection demand is denoted by its source node s and destination node d by (s, d). No wavelength conversion function is assumed at nodes since they are very expensive. We assume that all connection demands are full-duplex, i.e., each demand requires a pair of unidirectional paths, i.e. (s, d) and (d, s). We assume that each pair of paths uses the same route but in opposite directions for mesh networks. If we need to establish multiple paths between s and d, the number of (s, d) and (d, s) will be equal to that of paths. Throughout this paper, the demand sets, i.e., demand edge node pairs, are denoted by X. Necessary number of frequency slots is determined by the required level of optical signal to noise ratio (OSNR). OSNR depends on the transmission distance and the number of nodes passed. An example of the relationship between hop count and necessary number of frequency slots in a regular mesh network, i.e. uniform link lengths, is shown Fig. 1 [1]. The number of frequency slots needed exhibits a stepwise behavior, since we select the modulation format according to the number of hops [21].

3. Design Algorithms for Ring Networks with 1+1 Dedicated and 1:1 Shared Protection

In this section, we propose two algorithms for SLICE ring networks with distance adaptive modulation. We assume two protection schemes: 1+1 dedicated protection and 1:1 shared protection. The former assigns a dedicated backup path to each working path. The latter assigns a backup path to each working path and wavelengths on each link for backup paths can be shared among multiple backup paths whose working paths do not share any link. One algorithm is for the 1+1 dedicated protected 2-fiber ring networks while the other is for the 1:1 shared protected 2-fiber ring networks. We assume that, for each pair of working/backup paths, two transponders/receivers are used at their source/destination nodes. This assumption guarantees survivability for single transponder/receiver failure in addition to the link/node failures along the path. It also enables us to assign different frequency slot sets to working/backup paths. For ring networks, there are only two route candidates for each path connection demand; clockwise and counterclockwise directions. If one of the two candidate directions is assigned to a working path, the other must be used for its backup path. For 1+1 dedicated protected network design, for each demand, both the working path and the backup path need dedicated frequency slots on each respective link. For 1:1 shared protected network design, we accommodate given demands sequentially. In the process of accommodating each demand, we search for a group of the other working paths that have yet to be accommodated and whose routes do not overlap with that of the working path being considered. The backup path of the considering working path and backup paths of the other working path group should share frequency slots as much as possible so that we can maximize frequency utilization efficiency.

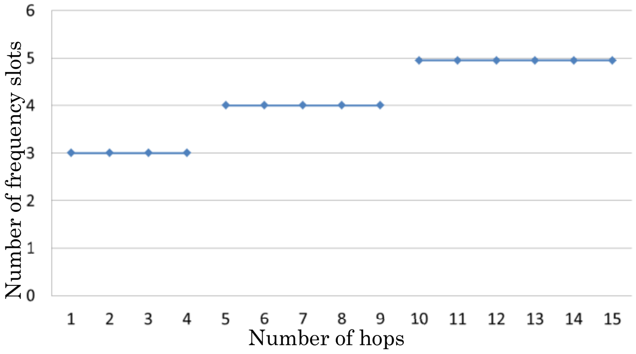


Fig. 1 Variation in number of frequency slots needed [1].

⟨Design algorithm for 1+1 Dedicated Protected 2-Fiber Bidirectional Ring Networks⟩

Step 1. Among the set of demands not accommodated yet, select a pair of unidirectional paths $\{(s, d), (d, s)\}$ that connects the pair of nodes s, d in the opposite direction.

Step 2. For the pair of path demands, selected in Step 1, assign the shortest routes to their working paths and the remaining routes to backup paths. Lengths of node distances between s and d may be the same for clockwise and counterclockwise directions; select one randomly and assign it to the working path. Assign the same frequency slot sets that have the minimum slot index among all possible slot sets to the pair of working path and its backup path.

Step 3. Repeat Step 1 and Step 2 until all the demands are accommodated.

⟨Design algorithm for 1:1 Shared Protected 2-Fiber Bidirectional Ring Networks⟩

Step 1. For each path connection demand, assign the shortest route to the working path and the alternative route in the opposite direction to the backup path. When the lengths of working and backup path candidate routes are identical, select one randomly and assign it to the working path.

Step 2. Find the set of demands in X not accommodated yet and whose working paths do not overlap through the following procedure. Select the connection demand x with the longest working path length among the demands not accommodated yet. Let $X_0 = \{x\}$. In descending order of working path length, find a demand $y \notin X_0$ that is not accommodated yet and that does not share any link with any of the working paths of the demands in X_0. Let $X_0 = X_0 \cup \{y\}$. Repeat this procedure until no demand remains.

Step 3. For the demand set X_0 selected in Step 2, assign the same frequency slot set to the working paths where the number of slots is determined so as to satisfy the OSNR requirement for the longest path. Similarly to the process for working paths mentioned above, set the common frequency slot set, which can be different from the one for the working paths, to their backup paths.

Step 4. Repeat Step 2 and Step 3 until all demands are accommodated.

4. Design Algorithm Based on a Multi-Stage ILP Optimization for Mesh Networks

In this section, we propose an algorithm for mesh networks without protection. The introduction of path protection in mesh networks requires more than twice the necessary network resources. As a result, for long-haul network application, protection in the client layer is currently the dominant approach (IP fast reroute or multiprotocol label switching traffic engineering (MPLS-TE) fast reroute, for example), which is different from shorter transmission distance metro networks which utilize protected ring networks for their very short failure recovery times. As a first step, we investigate non-protected mesh networks to verify the impact of SLICE distance adaptive modulation. Even though we do not consider distance adaptive modulation, routing and frequency slot assignment is a computationally hard task since it is equivalent to routing and wavelength assignment in conventional optical path networks which is known to be NP-complete [23], i.e. the most computationally intractable of class NP (Nondeterministic Polynomial time) problems [24]. In this paper, we take the approach of separating the routing and the frequency slot assignment process to make the problem tractable. The non-uniform frequency slot assignment makes it difficult to densely pack reserved slot sets at each link. Some gaps between reserved slot sets are inevitable. In order to mitigate the loss in frequency resource utilization, we divide the design process so that we can pursue the allocation of paths group by group; paths in one group need the same number of frequency slots on the shortest routes. Using this approach, we can minimize the spectrum fragmentation in each link by unifying the necessary bandwidth for paths. We formulate a multi-stage ILP for routing, where each stage is an ILP defined for a set of paths that need the same number of slots.

⟨Multi-stage routing and frequency slot assignment for mesh networks⟩

Step 1. For each demand, calculate the necessary number of frequency slots that are necessary to traverse the shortest route between the source and destination. Classify all path demands into groups with the number of frequency slots necessary; i.e. each group consists of demands that require the same number of frequency slots.

Step 2. Routes of the demands are assigned in a group by group manner and the objective is to minimize the number of incremental fibers at each assignment stage. Let the demand groups be ordered in ascending number of frequency slots necessary. For each group, complete route assignment of demands in the group such that the number of additional fibers needed to accommodate the demands is minimized. If, for a demand, the number of slots necessary to traverse the assigned route is less than that of the group, move the demand to a group whose number of slots necessary is identical to that of the demand. If, for a demand, the number of slots necessary to traverse the assigned route is larger than that of the group, cancel the route assignment for the demand and move the demand to a group whose number of slots necessary is identical to that of the demand.

NOTE: The capacity of fiber is modified by multiplying it by a constant ($\leq$ 1). Since, in the above route assignment, we do not consider frequency slot collision among paths, additional capacity will be necessary for each fiber to accommodate the demands and to avoid the collision. How to determine the constant is discussed in Sect. 5.3.

Step 3. Assign frequency slots sequentially to demands in descending order of path length. The search for vacant frequency slots is done in the first-fit manner. If no frequency slots are available that are common to all links on the route due to the frequency collision, add the minimum number of fibers and accommodate the demand. Repeat this procedure until all demands are accommodated.

5. Numerical Experiments

We evaluated the improvement in spectrum utilization efficiency achieved using SLICE, which adopts distance adaptive modulation (DA-SLICE), compared to two other methods: assignment based on ITU-T grid (ITU-T grid-based) and SLICE without distance adaptive modulation (nonDA-

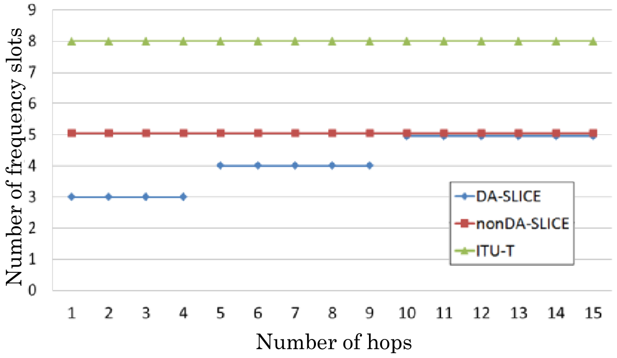


Fig. 2 Required number of frequency slots and optimum modulation format as a function of the number of node hops.

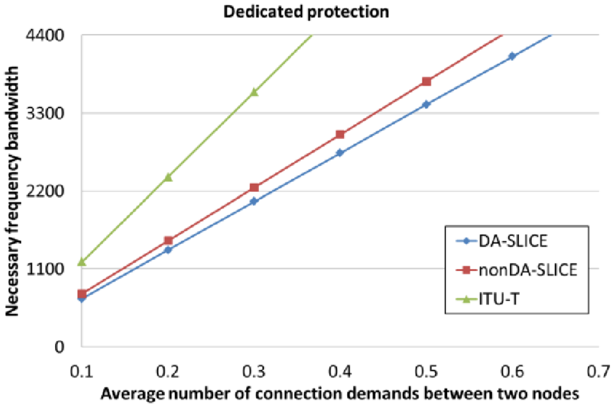


Fig. 3 Variation in utilized bandwidth.

SLICE) where the modulation format is fixed to that necessary to traverse the maximum distance. We assumed that the frequency slot width is 12.5 GHz and the available frequency bandwidth in a fiber is 4,400 GHz, i.e., the C-band. Figure 2 shows the required number of frequency slots and the optimum modulation format as a function of the number of node hops for each spectrum assignment method used in our evaluation. We obtained this frequency slot allocation map by numerically simulating the transmission performance for various sets of parameters, i.e., modulation formats and filter 3-dB widths, taking into account optical SNR degradation and the optical-filter narrowing effect. We assumed single-carrier dual-polarized 112-Gb/s signal transmission through optical nodes interconnected with 50-km-long standard single-mode fiber links. Details regarding the conditions of the simulation are given in [1]. It should be noted that the spectrum requirements depend on various node and network conditions and the spectrum allocation map shown in Fig. 2 is just an example.

According to our simulation results, in the DA-SLICE approach, shorter optical paths with node hops of fewer than 5 require 3 frequency slots (37.5 GHz) rather than the usual 4 slots (50 GHz) if we utilize the spectrally efficient 16-ary quadrature-amplitude modulation (QAM) instead of quadrature phase shift keying (QPSK) modulation. On the other hand, longer paths with more than 9 node hops require 5 frequency slots (62.5 GHz) in order to ensure an acceptable pass band at the egress optical node. In contrast, if we employ the traditional worst-case network design approach, where a modulation format and a filter bandwidth are selected so that the worst-case optical path in the network can be transmitted with sufficient quality, the nonDA-SLICE approach requires 5 frequency slots (62.5 GHz) for all paths regardless of the number of node hops. In addition, since the conventional 50-GHz ITU-T grid cannot accommodate the number of paths for the worst case, ITU-T grid-based networks should be designed based on the 100-GHz ITU-T grid, meaning that 8 frequency slots (100 GHz) should be assigned to every path.

Connection demands were randomly and uniformly distributed in the network. The average number of connection demands between two nodes is the number of paths established in the network, and is calculated as the product of average number of paths between each node pair and the number of node pairs in the network. Each source and destination node pair is uniformly and randomly selected for each path to determine the traffic demand matrix. For each traffic demand, five different demand patterns are generated and the results shown hereafter are the ensemble average of the obtained results.

5.1 1+1 Dedicated Protected 2-Fiber Bidirectional Ring Network

In this section, we assume a 2-fiber bidirectional ring network that consists of 16 nodes and the link length between nodes is set at 50 km. Each connection utilizes two transponders for working and backup paths, as mentioned before, which allows us to assign different numbers of frequency slots to each of the paths. The variation in occupied number of slots for 1+1 dedicated protected 2-fiber bidirectional ring network is shown in Fig. 3. The maximum value on the vertical axis, 4400 GHz, represents the available bandwidth in the C-band. Since the optimal optical routing and wavelength/frequency slot assignment for 1+1 dedicated protection ring networks is to allocate the same wavelength/frequency slot to each pair of path demands between node pairs, the ratio of spectrum usage of ITU-T and nonDA-SLICE is exactly the same as the ratio of number of frequency slots given in Fig. 2. Figure 3 shows that the proposed method reduces the necessary frequency slots by about 9%/43% compared to nonDA-SLICE/ITU-T in 1+1 dedicated protection ring networks.

5.2 1:1 Shared Protected 2-Fiber Bidirectional Ring Network

The evaluation conditions such as a network topology are same as those in Sect. 5.1. The variation in occupied number of slots for 1:1 shared protected 2-fiber bidirectional ring network is shown in Fig. 4. As for ITU-T, we employed the multi-stage ILP formulations presented in the Appendix to derive the optimal routing and wavelength

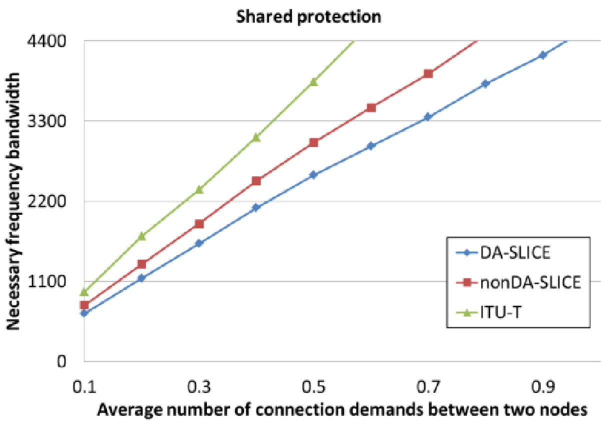
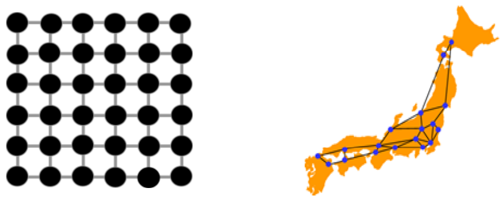
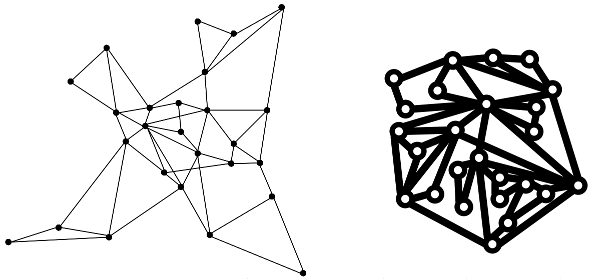


Fig. 4 Variation in utilized bandwidth.



(a) 6x6 polygrid network (b) Japan's backbone



(c) COST266 network (d) French network

Fig. 5 Topologies.

assignment for 1:1 shared protection ring networks. As for nonDA-SLICE, we applied the same algorithm as DA-SLICE. Figure 4 verifies that the proposed method reduces the frequency slots needed by about 14%/33% compared to nonDA-SLICE/ITU-T grid in 1:1 shared protection ring networks.

Table 1 6 × 6 polygrid network.

Number of nodes		36
Node degree	Min	2
	Max	4
	Ave	3.3
Number of links		60
Number of hops	Min	1
	Max	10
	Ave	4

Table 2 Japan's backbone network model.

Number of nodes		18
Node degree	Min	2
	Max	5
	Ave	3.3
Number of links		30
Number of hops	Min	1
	Max	7
	Ave	2.8

Table 3 COST266 network.

Number of nodes		26
Node degree	Min	2
	Max	8
	Ave	3.9
Number of links		51
Number of hops	Min	1
	Max	6
	Ave	2.8

Table 4 French network.

Number of nodes		25
Node degree	Min	2
	Max	10
	Ave	3.6
Number of links		45
Number of hops	Min	1
	Max	5
	Ave	2.6

Table 5 Distribution of paths.

	3 slots (%)	4 slots (%)	5 slots (%)
6x6	61.9	37.8	0.3
Japan	86.3	13.7	0.0
COST266	92.9	7.1	0.0
France	97.7	2.3	0.0

5.3 Mesh Networks

We applied our proposed methods to the backbone network such as 6 × 6 polygrid network, Japan's backbone network model, COST266 Pan-European network, and the French backbone network model, where all link lengths are uniformly fixed at 50 km (Fig. 5). Tables 1–4 shows the characteristics of those networks. Table 5 shows the distribution of paths with different slot assignment in each topology. We also introduce a simple sequential heuristic method denoted by "Heuristic" for DA-SLICE networks. This method assigns a pair of route and slot indexes sequentially to each path in descending order of shortest hop count. For each assignment, the method searches for a route and a slot index pair among the route candidate set, the set of all routes that needs the same number of slots to traverse, that minimizes the fiber increment. This method is simple and is often used for designing conventional ITU-T grid-based networks. However, it is based on path by path minimization of cost increment, i.e. sequential local optimization, and hence the performance enhancement is limited compared with the

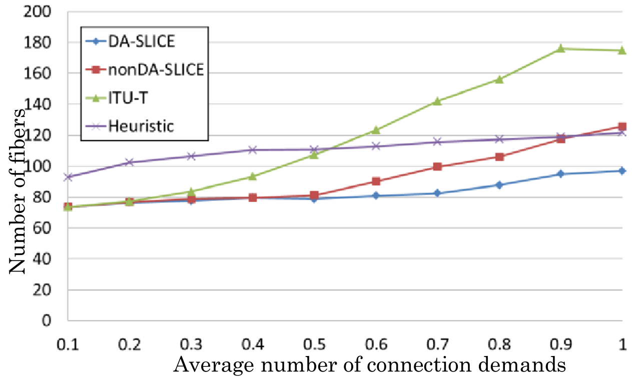


Fig. 6 Impact of proposed method in 6 × 6 polygrid network.

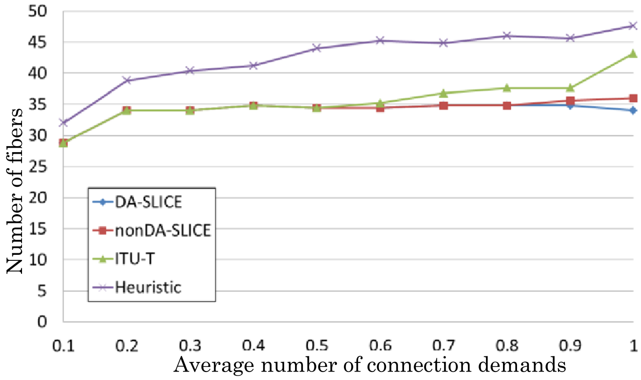


Fig. 7 Impact of proposed method in Japan’s backbone network model.

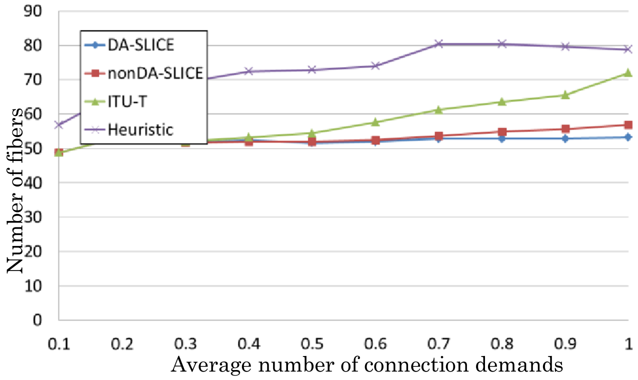


Fig. 8 Impact of proposed method in COST266 network.

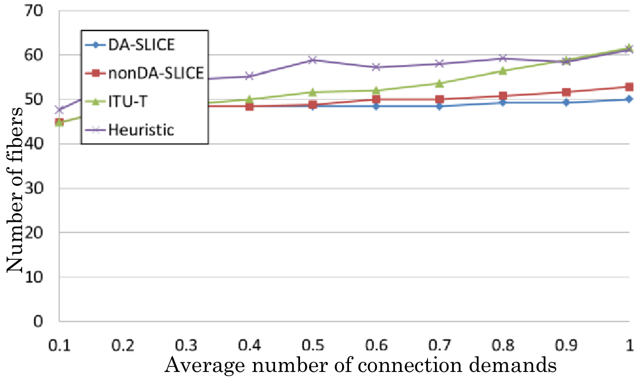


Fig. 9 Impact of proposed method in French network.

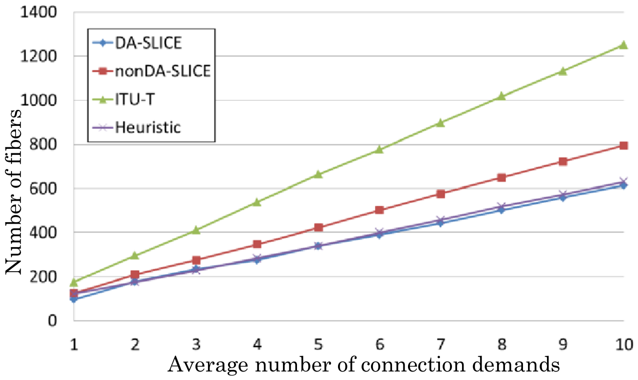


Fig. 10 Impact of proposed method in 6 × 6 polygrid network.

simultaneous optimization of all paths, including the proposed method. Regarding our proposed algorithm, we set the constant multiplied to fiber capacity in Step 2 of the proposed algorithm at 0.8, which means that we provide 20% margin in terms of fiber capacity used in the ILP formulation. We investigated the impact of the constant on various situations, and as a result we found that setting the value to 0.7–0.9 gives good results and we selected the value of 0.8 since it attains best result for almost all cases. Figures 6–13 demonstrate the effectiveness of our proposed method in different topologies, where the demand intensity, average number of connection demands, is changed. Figures 6–9 plot the results for small traffic demand, while Fig. 10–13 serves large traffic demand. In the small demand area, the fiber capacity is enough to accommodate the requested bandwidth even in the ITU-T scheme. However, as the traffic increases, the impact of SLICE with distance adaptive modulation strengthens. DA-SLICE can reduce the number of fibers by over 50% when the average number of connection demands is 10 compared to ITU-T. DA-SLICE reduces the number of fibers needed more than Heuristic especially in the small demand area. For mesh networks, in order to accommodate full-duplex connection, each connection consists of a pair of unidirectional paths that use the same route but in opposite directions. This means that each link consists of an even number of fibers. For the small traffic demand area, for example the demand of 0.1, the fibers are sparsely utilized and the proposed algorithm minimizes the number of fibers by detouring some paths.

However, in order to guarantee the connectivity between node pairs, the number of fibers cannot be much less than twice of the number of links. Indeed, the number of fibers for the demand of 0.1 is 80, which means that up to 40 links among 60 links are used since further fiber reduction is not possible. However, as traffic volume increases, the gap between DA-SLICE and Heuristic becomes small, and Heuristic will be an efficient alternative if the average number of paths between two nodes is larger than one since Heuristic has much lower computational cost. For example,

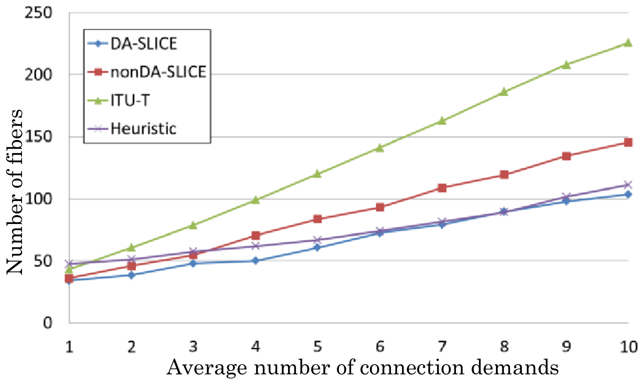


Fig. 11 Impact of proposed method in Japan's backbone network model.

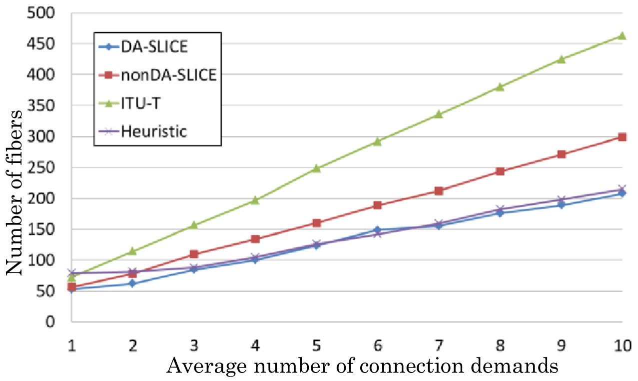


Fig. 12 Impact of proposed method in COST266 network.

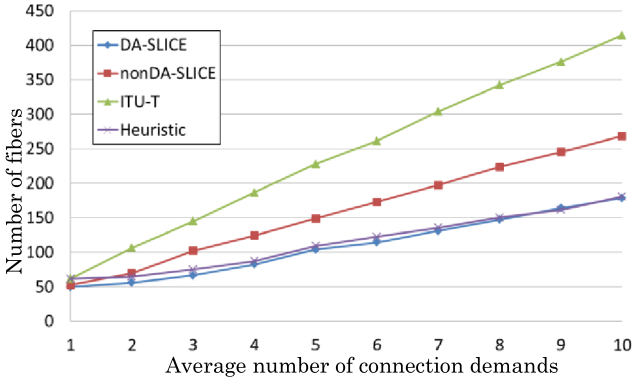


Fig. 13 Impact of proposed method in French network.

when the average number of paths is 10 in the 6×6 polygrid network, the calculation time of DA-SLICE using ILP took more than one day (duality gap was then 1.5%), while the calculation time of Heuristic was around one minute.

6. Conclusion

This paper proposed three routing and frequency slot assignment algorithms for 1+1 dedicated/1:1 shared protected 2-fiber bidirectional ring networks and for mesh networks that utilize SLICE with distance adaptive modulation. The resource reduction effect in terms of frequency spectrum width and the number of fibers was quantitatively verified through several numerical experiments. The results showed that the necessary frequency bandwidth was reduced by 43%/33% in 1+1 dedicated/1:1 shared protected ring networks. For mesh networks, it was found that 50% or more traffic can be accommodated with SLICE technologies.

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Appendix

7.1 ILP based design of 1:1 shared protected 2-fiber bidirectional ring networks

An ILP formulation of the routing and wavelength assignment problem of 1:1 protected ring networks is given below. This formulation is a modified version of [25] that considers the design of unprotected ring networks.

Notations

Symbols

G=(V, E): Given graph.

V: The set of all nodes.

E: The set of all directed links.

R=$\{1, 2\}$: The rotation direction of links (1: clockwise, 2: counterclockwise).

W: The set of all wavelength indexes.

K: The set of all traffic demands, where each demand is a request for wavelength path establishment from a given source node to a given destination node.

Binary variables

$x^r_{k,w}$: If a path for demand k is established using $route(k, r)$ and wavelength w, $x^r_{k,w} = 1$. Otherwise $x^r_{r,w} = 0$.

v^r_w: If wavelength w is used to establish paths in direction r, $v^r_w = 1$. Otherwise $v^r_w = 0$.

U_w: If wavelength w is used by some paths, $U_w = 1$. Otherwise $U_w = 0$.

Functions

rot: A function that returns the identifier of direction in R for the given directed links.

route: A function that computes a route of given traffic demand in given rotation direction, and returns a sequence of the identifiers of the contiguous directed links.

$K_e = \{k \in K | e \in route(k, rot(e))\}$: The set of traffic demands going through a directed link e.

Objective

Minimize: QUOTE $\sum_{\mathrm{w}\in\mathrm{W}} \mathrm{U_w}$ (i.e. Minimization of the number of wavelengths used)

Subject to the following constraints:

- Establishment of all demands
  $\sum_{w\in W} x^1_{k,w} + x^2_{k,w} = 1$ for all $\mathrm{k} \in \mathrm{K}$
- Wavelength conflict restriction
  $\sum_{\mathrm{k}\in\mathrm{K_e}} \mathrm{x^{rot(e)}_{k,w}} \leq 1$ for all $w \in W$ and $\mathrm{e} \in \mathrm{E}$
- Protection resource reservation
  $x^{rot(e)}_{k,w} \leq v^{rot(e)}_w$ for all $\mathrm{k} \in \mathrm{K}$, $\mathrm{w} \in \mathrm{W}$ and $\mathrm{e} \in \mathrm{E}$ $v^1_w + v^2_w \leq U_w$ for all $\mathrm{w} \in \mathrm{W}$

7.2 Proposed multi-stage ILP based design of mesh networks

A multi-stage ILP formulation on routing in mesh networks is given below. This formulation is a modified version of [26] that considers the design of virtual wavelength path networks that assume wavelength conversion.

Notations

Symbols

G=(V, E): Given graph.

V: The set of all nodes.

E: The set of all directed links.

T: The set of indexes for demand groups where each group is consisted of the set of demands that the number of frequency slots necessary for their shortest routes are same.

M: The maximum number of frequency slots in a fiber.

R: A constant to reduce fiber capacity (See Step 2 of proposed algorithm in Sect. 4).

Integer variables

$D_{s,d}$: Number of connection demands from node s to node d.

$F_{i,j}$: Number of fibers from node i to node j.

$f_{s,i,j}$: Number of paths on link *(i, j)* whose source node is s.

$B_{i,j}$: Residual fiber capacity after previous group optimization on link (i, j).

S_t: Number of frequency slots necessary for the groupt.

Objective

Minimize: $\sum_{\mathrm{i,j}} \mathrm{F_{i,j}} + \frac{\mathrm{S_t}}{\mathrm{M}} \sum_{\mathrm{s,i,j}} \mathrm{f_{s,i,j}}$

Subject to the following constraints:

- Source node constraints
  $\sum_i f_{s,s,i} = \sum_j D_{s,j}$ for all $s \in V$
- Intermediate node constraints
  $\sum_{\mathrm{i}} \mathrm{f_{s,i,k}} - \sum_{\mathrm{j}} \mathrm{f_{s,k,j}} = \mathrm{D_{s,k}}$ for all $\mathrm{s, k} \in \mathrm{V}$
- Capacity constraints
  $\sum_{\mathrm{s}} \mathrm{f_{s,i,j}} \leq \frac{\mathrm{R}}{\mathrm{S_t}} \cdot (\mathrm{M} \cdot \mathrm{F_{i,j}} + \mathrm{B_{i,j}})$ for all link $(i, j) \in E$

- Full duplex connection
  $f_{s,i,j} = f_{s,j,i}$ for all $s \in V$ and $(i, j) \in E$

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