Capacity-Bound Evaluation and Routing and Spectrum Assignment for Elastic Optical Path Networks with Distance-Adaptive Modulation

Kenji Cruzado[1], Yojiro Mori[1], Shih-Chun Lin[2], Motoharu Matsuura[3], Suresh Subramaniam[4], Hiroshi Hasegawa[1]

[1]Nagoya University, Furo-cho, Chikusa, Nagoya, 464-8603, Japan
[2]North Carolina State University, Raleigh, NC 27695 USA
[3]The University of Electro-communications, 1-5-1 Chofugaoka, Chofu, Tokyo, 182-8585 Japan
[4]The George Washington University, 800, 22nd St. NW, Washington DC, 20052 USA
cruzado.kenji.p5@s.mail.nagoya-u.ac.jp

Abstract: A novel and effective network capacity estimation method and an RSA algorithm suitable for elastic optical path networks are presented. The proposed algorithm successfully achieves the utilization penalty of just 5-16% from the bound. © 2024 The Authors

1. Introduction

Given the recent advancements in software-defined networks (SDNs) [1], and the widespread adoption of 5G and beyond 5G mobile communications [2], forthcoming optical networks are expected to adopt dynamic path control and elastic optical networking to enable flexible and agile resource allocation. Such resource allocation in optical networks can overcome the severe need for capacity enhancement to cope with the recent exponential and sustained growth of IP traffic. Estimating how much traffic can be accommodated by a network has been a longstanding topic. For example, capacity bound estimation methods for electrical packet switching networks, such as Asynchronous Transfer Mode (ATM) cell networks [3], have been proposed. However, no such methods for optical networks have been proposed so far as the inherent constraints of optical transparent transmission prevent us from applying the same methodology created for electrical packet/cell switching networks.

Fortunately, recent advancements in machine learning (ML) have positioned ML as a promising approach for the design and control of optical path networks that offer efficient resource allocation [4–6]. For the essential task in the design and control of optical path networks, routing and spectrum/wavelength assignment (RSA/RWA), most current studies on ML-based methods adopt the simplest heuristics called k-shortest path first-fit (KSP-FF) as the benchmarking alternative; a route is initially selected and then a search for available frequency slots for each path to be established is applied. However, the performance of such RSA/RWA heuristics heavily rely on the search order of pairs of routes and spectrum/wavelength slot sets to be assigned. Therefore, improvements over the heuristics approach with different ordering have to be examined to better assess the effectiveness of ML-based RSA/RWA algorithms.

We have recently proposed a capacity estimation method that adopts link cut-set load estimation [7]; its effectiveness was confirmed by using simple fixed-grid optical networks. By extending this preliminary study, this paper proposes a novel capacity estimation method that can be applied to elastic optical path networks with distance-adaptive modulation. The method finds cut-sets that are expected to be heavily loaded. The capacity bound is then estimated as a blocking ratio evaluation on selected cut-sets. We also propose a novel RSA algorithm that aims to suppress the utilization ratios of the heavily loaded cut-sets. Numerical simulations on several topologies elucidate that KSP-FF, often used as a benchmark alternative to ML-based methods, underperforms the other heuristics with different search orderings. In most cases, our algorithm achieves the best performance among all examined methods. Moreover, the gap between the best performance and the evaluated effective network capacity is in the range of 5-16% which shows that the room for further capacity enhancement by the introduction of ML is quite limited for future agile elastic optical path networks with distance-adaptive modulation.

2. Proposed Capacity Estimation and RSA for Elastic Optical Path Networks

We assume transparent optical path networks that adopt the ITU-T flexible grid [8], and distance-adaptive modulation [9]. Single mode fibers are laid on each link. The expected number of paths to be established between nodes, i.e., traffic distribution, is assumed to be known. The discussion in this paper can easily be extended to networks that adopt multi-band transmission and/or spatial division multiplexing.

The stochastic behavior of networks with fine granularity packet/cell switching can be accurately estimated and the highest congestion level of link cut-sets gives the exact packet/cell drop ratio variation in the network. As one of the cut-sets always has the highest congestion level for any given traffic distribution, the drop ratio variation can be easily estimated [10]. On the other hand, the path granularity routing and the spectrum/wavelength continuity in transparent optical networks makes the modeling of stochastic behavior inaccurate. Thus, we propose an alternative approach that introduces the evaluation of multiple cut-sets and numerically estimates the correlation of the congestion.

<Effective Capacity Estimation Method for Elastic Optical Networks>

Step 1. Finding Congested Cut-sets

Find all cut-sets [11]. Let V be the set of all nodes in the given topology, C_n be the n th cut-set, S_n be the set of nodes in a sub-graph separated by C_n, and $V\backslash S_n$ be the set of nodes in the other subgraph separated by C_n. Let $slot(s,d)$ $(s \in S_n,\ d \in V\backslash S_n)$ be the averaged slot number occupied by a path from s to d; here we assume that all the paths from s to d go through their shortest route so that the modulation format with the highest possible order can be used (Fig. 1). We calculate the congestion level of the n th cut-set, w_n, by

$$w_n = \sum_{s \in S_n, d \in V\backslash S_n} \frac{T(s,d)slot(s,d)}{\sum_{i \in Cn} f_n^i}, \tag{1}$$

where $T(s,d)$ are the expected path setup requests from s to d that arrive per unit time, and f_n^i is the number of fibers on the i th link in the n th cut-set whose ingress and egress nodes are respectively located in S_n and to $V\backslash S_n$. Select several cut-sets with large congestion level values and let C_{heavy} be the set of these selected cut-sets.

Step 2. Capacity Estimation

Generate path setup requests stochastically according to the given traffic distribution, where the selection of modulation formats is changed to suit the transmission impairment levels. For each path setup request, search cut-sets in C_{heavy} such that the source and destination of the path distribute to the opposite sides of these cut-sets. Then, find a commonly unused frequency slot sets in all the cut-sets found. If found, assign the frequency slots to the path. Otherwise, the path setup request is blocked. The number of paths thus accommodated by the network gives the estimated capacity bound.

Based on the cut-set load analysis, an RSA algorithm for path setup in elastic optical networks is developed. In the static network design case, the algorithm is iteratively applied until all setup requests are processed. In the dynamic control case, in addition to the straight-forward path removal procedure, the algorithm is applied to each arrival of path setup request.

<Design and Control Algorithm for Elastic Optical Path Network>

For each path setup request, identify the route candidates using the k-shortest path algorithm. Search for available pairs of route and frequency slots from the smallest slot index. If no pair is obtained, increment the index of frequency slots and search again. If no available pair is obtained after searching all frequency slot indices, reject the path setup request. If multiple available pairs are found, for each candidate route, obtain all cut-sets in C_{heavy} that the route candidate traverses. For each route candidate, calculate the sum of congestion level w_n for obtained cut-sets. Then select the pair that minimizes the sum of congestion level w_n (Fig. 2).

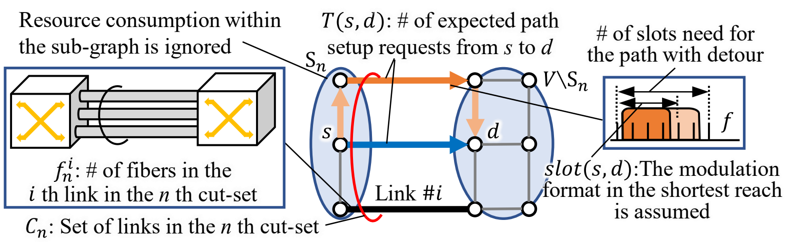

Fig. 1. Parameters used to identify cut-set expected to be congested.

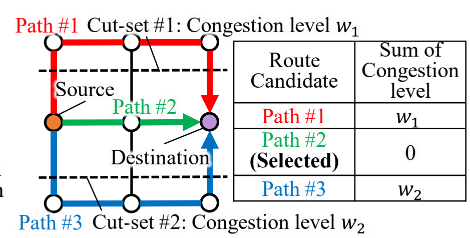

Fig. 2. Proposed RSA algorithm.

3. Numerical Simulations

We numerically simulated four topologies, Pan-European COST266, British Telecom Network, Japan JPN12 and German Network to verify the capacity upper bound and the performance of the conventional heuristics and proposed algorithm in dynamic path control scenarios. A pair of optical fibers of opposite directions is laid on each link. The adoption of a flexible grid with distance-adaptive modulation is assumed. The available frequency range for all fibers was set to 4.8 THz / 384 with 12.5GHz-wide frequency slots. The requested data rate for each path was randomly selected from 100 Gbps, 400 Gbps, and 1 Tbps with equal probabilities. The numbers of slots needed for paths were selected according to Table 1. Path setup requests were dynamically generated randomly following a Poisson process, and their durations were modeled using a negative exponential distribution. The traffic intensity was regulated by alternating the average lifetimes between setup and teardown requests. We employed the k-shortest path algorithm to enumerate route candidates, with the predetermined maximum of 50 candidates. Subsequently, we used the k-shortest path first-fit (KSP) and congestion aware (CA) for route selection. Frequency slot selection was carried out using the First-Fit (FF) method. We explored four possible combinations: KSP-FF, FF-KSP, CA-FF, and FF-CA. In the KSP-FF and CA-FF approaches, route candidates were fixed initially and available pair of route and frequency slots were searched, while the FF-KSP [12], and FF-CA methods initially set the frequency slots and searched for available pair of route and frequency slots.

Figure 3 shows the blocking ratio variations subject to traffic intensity change. We used the traffic intensity at the blocking probability of 10^{-3} as the performance metric. By comparing the proposal with the other heuristics, we confirmed that the proposal matches the best of the other methods. The room for improvement to FF-KSP or our proposal is limited to just 11% in COST266, 16% in British Telecom, 5% in JPN12 and 7% in German Network. This variation strongly depends on the location of each congested cut-set. Since routing is omitted in the capacity estimation, the paths have more alternatives in which to be accommodated. If a path traverses congested cut-sets that cross each other, the capacity is overestimated, because the resource allocation may be deviate from actual RSA/RWA.

Table 1. The number of slots needed to accommodate each optical path.
(Maximum transmissible distances are 1200 km for 8QAM and 600 km for 16QAM.)

	100 Gbps	400 Gbps	1 Tbps
QPSK	4 slots	12 slots	28 slots
8QAM	3 slots	9 slots	19 slots
16QAM	2 slots	7 slots	12 slots

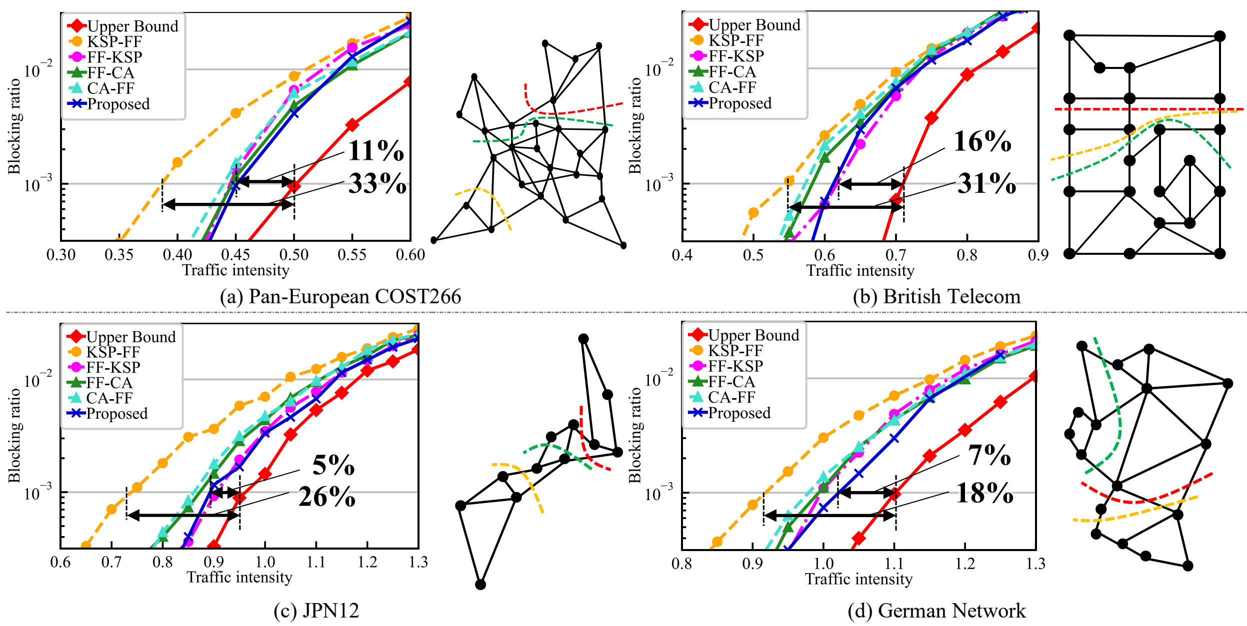

Fig. 3. Blocking ratio of proposed and conventional methods with topologies and congested cut-sets.
(Red broken line: 1st congested, Orange broken line: 2nd congested, Green broken line: 3rd congested)

4. Conclusion

We proposed a novel capacity estimation method for elastic optical networks with distance-adaptive modulation and an RSA algorithm that is aware of the utilization of cut-sets that are expected to be heavily loaded. Numerical simulations on several topologies elucidated that KSP-FF, often used as a benchmark alternative to ML-based methods, underperforms the other methods. The other heuristics with different search orderings achieve much better performance and our algorithm achieves the best performance in most cases. The gap between the best performance and the evaluated effective network capacity is in the range of 5-16% which shows that the room for further capacity enhancement by the introduction of ML to RWA/RSA is quite limited.

Acknowledgment: This work is partly supported by NICT (22402).

5. References

[1]D. Kreutz *et al*., Proceeding IEEE, **103**, 14-76 (2015)
[2]A. Dogra *et al*., IEEE Access, **9**, 67512-67547 (2021)
[3]R. Guerin *et al*., IEEE J. Selected Areas Commun., **9**, 968-981 (1991)
[4]X. Chen *et al*., IEEE J. Lightwave Technol., **37**, 4155-4163 (2019)
[5]L. Xu *et al*., IEEE J. Lightwave Technol., **40**, 4945-4955 (2022)
[6]S. Nallaperuma *et al*., IEEE J. Opt. Commun. Netw., **15**, 497-506 (2023)
[7]K. Cruzado *et al*., PSC (2023)
[8]ITU-T Recommendations G694.1 (2012)
[9]M. Jinno *et al*., IEEE Commun. Magazine, **48**, 138-145 (2010)
[10]R. Roy *et al*., IEEE J. Opt. Commun. Netw., **2**, 256-265 (2010)
[11]K. Hayashi *et al*., IEEE J. Opt. Commun. Netw., **15**, D23-D32 (2023)
[12]R. J. Vincent *el al*., IEEE J. Lightwave Technol., **37**, 5380-5391 (2019)