Dynamically Controlled Flexible-Grid Networks Based on Semi-Flexible Spectrum Assignment and Network-State-Value Evaluation

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Abstract: We propose a novel RSA algorithm for dynamically-changing flexible-grid networks. The proposed scheme can suppress spectral fragmentation and adapt to traffic-distribution change. Extensive simulations show that the fiber-utilization efficiency is increased by 1% to 57%.

1. Introduction

The growth in IP traffic has been recently accelerated by rapidly emerging video-streaming services and cloud-computing services. Current networks typically offer 100 Gbps channels located on the 50 GHz grid; in contrast, the next-generation channels such as 400 Gbps and 1 Tbps will utilize broader frequency bandwidths. This motivates us to introduce flexible-grid networks in which a finely granular frequency grid is used to allocate the minimum frequency bandwidth to each channel [1]. However, the non-uniformity in channel frequency bandwidths results in spectral fragmentation that degrades fiber utilization over the network. Accordingly, routing and spectrum assignment (RSA) algorithms to suppress the spectral fragmentation are being extensively studied [2-6]. On the other hand, the advent of 5G services and construction of hyper-scale data centers will drastically change the traffic distribution. In such cases, routing must be carefully conducted to handle the mismatch between the already deployed fiber arrangement and the changed traffic distribution, otherwise specific links will tend to be congested. Therefore, a novel RSA algorithm that can simultaneously avoid spectral fragmentation and link congestion will be needed to realize higher fiber-utilization efficiency in the dynamically-changing flexible-grid networks expected in the near future.

In recent years, the application of machine learning (ML), not only to design and control of optical networks but also to optical transmission [7-9], has been making remarkable progress. In the pioneering study [7], a cognitive and autonomous RSMA (RSA with modulation-format selection) algorithm based on deep reinforcement learning was reported, wherein an agent learns successful policies from dynamic network operations. The agent takes the status of all frequency slots in a network as the input vectors to a neural network (NN); typical configurations would have numerous vectors (over 10000). On the other hand, we have already proposed an alternative formulation that enables substantial dimension reduction of the input vectors (~100) though its application was limited to fixed-grid networks [10]. It would be desirable to apply the scheme to flexible-grid networks while keeping the dimension of the input vectors small.

Given this background, we propose a novel RSA algorithm that can increase fiber-utilization efficiency in dynamically-changing flexible-grid networks. The proposed RSA scheme combines semi-flexible spectrum assignment with network-state-value evaluation. First, to relax the computational complexity of the ML process, we adopt semi-flexible spectrum assignment in which each type of bitrate signal can be set only to the fixed grid that is equal to the minimum required slot width [11]. Since the grid interval for each bitrate channel can be regarded as a fixed grid, the number of input vectors is reduced (~100). Consequently, the ML process can be executed with feasible computation cost. In the learning process, the network-state value is calculated based on the number of path demands that can be accommodated by the presently unused frequency slots. RSA is then applied to each path so that the network-state value after optical-path setup is maximized. The effectiveness of the proposed RSA algorithm is verified by numerical simulations using various network parameters such as network topologies, traffic-churn rates, and traffic-demand distributions. The number of path demands accommodated to the examined networks is increased by 1% to 57% compared to the conventional RSA scheme based on a heuristic algorithm.

2. Proposed Routing and Spectrum Assignment for Dynamically-Changing Flexible-Grid Networks

2.1 Concept

Throughout this paper, we consider dynamic path-setup/teardown operations under traffic-growth scenarios with traffic churn. We assume that traffic distribution is characterized as the expected number of path demands between each node pair and can be sufficiently well estimated.

Ideally, the ML-based RSA can learn how to minimize spectral fragmentation and how to avoid link congestion in the case where the fiber arrangement and traffic distribution are mismatched [10]. However, applying this to the flexible-grid networks is hindered due to a large number of spectrum candidates. For example, we need to consider 370 candidates for flexible-grid networks instead of 25 candidates for fixed-grid networks if a 15-slot channel is assigned to 15 of 384 slots. Consequently, the learning process suffers from the curse of dimensionality [12], especially when the number of links is large. To alleviate this, we introduce semi-flexible spectrum assignment in which each specific-bandwidth channel is aligned to an equally spaced virtual grid [11]. Figure 1 illustrates an example, where three kinds of channels are located in the frequency domain. Each set of same bitrate channels are located in a fixed frequency width that is determined specifically to suit the channel bitrate. Since the grid interval for each bitrate channel can be regarded as a fixed grid, the number of input vectors is reduced, making the execution cost of ML computation feasible.

To avoid spectral fragmentation and link congestion in the case where the fiber arrangement and traffic distribution are mismatched, we introduce the metric named network-state value; it represents the number of path demands that can be accommodated by the presently available frequency slots and is estimated subject to the traffic distribution. Roughly speaking, higher network-state values denote that a larger number of optical path demands can potentially be accepted in the future. Then, RSA is applied to each path so to maximize the network-state value after optical-path setup.

2.2 *Proposed RSA Algorithm*

Let a real-valued variable be $u_{(g,p,l)}$, where g represents the index of a grid defined in the semi-flexible spectrum assignment, p the position of the grid, and l the index of a link. The value of $u_{(g,p,l)}$ is the ratio of unused capacity on link l on position p of grid g. For a selected pair (g,p), the state-value $v(s_{(g,p)})$ for a state, $s_{(g,p)}$ $(= u_{(g,p,l)}l)$, is the expected number of paths that can be additionally accommodated at position p of grid g. As the topologies are common for all (g,p), $v(s_{(g,p)}) = v(s_{(g',p')})$ holds for all (g,p) and (g',p'). The total network-state value, V, is defined as $V = \sum_{(g,p)} b(g)v(s_{(g,p)})$, where $b(g)$ is the spacing of g. During NN training, the state values are numerically estimated for pair (g,p) by conducting multiple simulations for the given traffic distribution, and the values are memorized by a common NN. This procedure is based on a typical reinforcement learning technique (*e.g.* temporal-difference method). The NN is trained with virtually generated datasets that follow the estimated traffic distribution if any traffic-distribution change is detected. After the completion of NN training, the network will accept path-operation requests.

Figure 2 illustrates a simple example of the RSA procedure, where 2-slot and 3-slot channels are considered. If a request of 3-slot-path setup from node#2 to node#0 arrives, a candidate of route and spectrum is tentatively assigned. Then, the states, $s_{(2,1)}$, $s_{(1,1)}$, and $s_{(1,2)}$, are changed by the tentative path accommodation and the network-state value V for the candidate is calculated. After executing the same procedure for all candidates, the pair of route and spectrum that offers the maximum network-state value is definitively assigned.

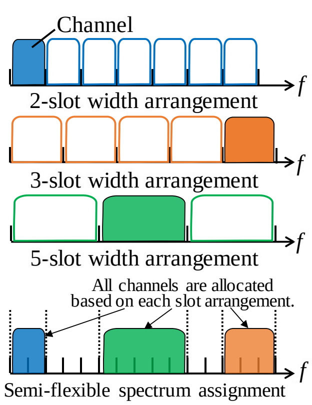

Fig. 1. Semi-flexible spectrum assignment, where three different types of channels are used as an example.

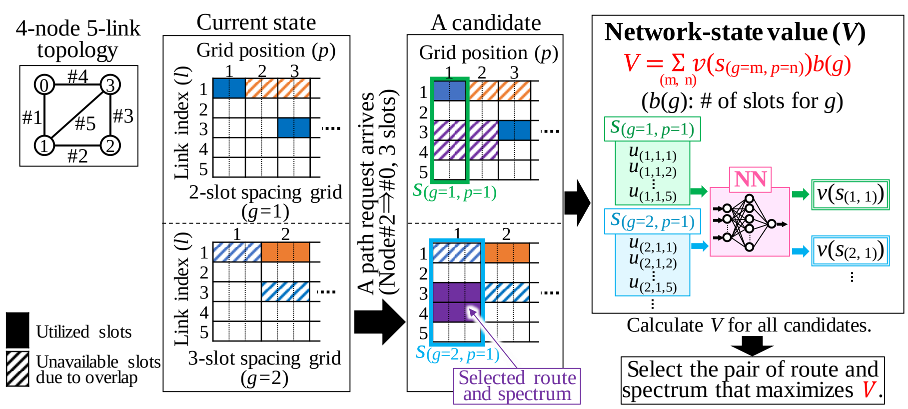

Fig. 2. An RSA process based on semi-flexible spectrum assignment and network-state-value evaluation, where 3-slot path request from node#2 to node#0 is assigned as an example.

3. Simulations

We evaluate the performance of the proposed RSA algorithm. The topologies tested are the DT17 and JPN12 networks. The number of 12.5 GHz slots per fiber is set to 384, *i.e.* 12.5-GHz-spaced grids in a 4.8 THz bandwidth are assumed. The bitrate for a path request is set to any one of 100 Gbps, 400 Gbps, or 1 Tbps and the corresponding slot width is

4, 7, or 15 slots. The number of fibers in each link is determined by static network design with a random traffic pattern generated according to a uniform distribution. The path setup and teardown requests arrive according traffic-growth scenarios with traffic churn. Path-teardown requests occur at the rates of 0.05, 0.10, 0.15, 0.20 relative to setup requests, the rate is parameterized as C. To emulate drastic changes in traffic distribution, we assume the centralized traffic distribution for the evaluation stage, where traffic concentrates on a selected node called the data-centric node. The data-centric node has 2, 3 or 4 times more path-setup requests than the other nodes do, request intensity is parameterized as I. Note that the traffic distribution differs from the one used to determine the number of fibers at each link. We use the above conditions in evaluating the performance of the proposed RSA (SF-NN). As references, we examine various RSA schemes based on heuristic algorithms: RSA with the first-fit criterion for full-flexible spectrum assignment (FF-FF), RSA with the target frequency for full-flexible spectrum assignment (FF-TF) [5], RSA with the first-fit criterion for semi-flexible spectrum assignment (SF-FF) [11], and RSA with the target frequency for semi-flexible spectrum assignment (SF-TF) [6].

Figure 3(a) shows the number of paths accommodated when the traffic-centric intensity I is 4 and the traffic-churn rate C is 0.2, where the data-centric node is changed. The proposed RSA scheme outperforms the reference methods in all cases. Figure 3(b) plots the number of paths accommodated where the traffic-churn rate C is 0.2 and the parameter is the traffic-centric intensity I. Figure 3(c) illustrates the number of paths accommodated when I = 4 and C is changed; the baseline is the performance of the FF-TF scheme that offers the highest performance other than the proposed scheme. We observe the impact of data-centric-node location; however, the proposed method outperforms the baseline methods. The fiber utilization efficiency is improved as the traffic-centric intensity I increases; in other words, the effectiveness of the proposed scheme is heightened when the mismatch between the fiber arrangement and the traffic distribution is large. The improvement in the fiber-utilization efficiency can reach 57% according to the tested network conditions.

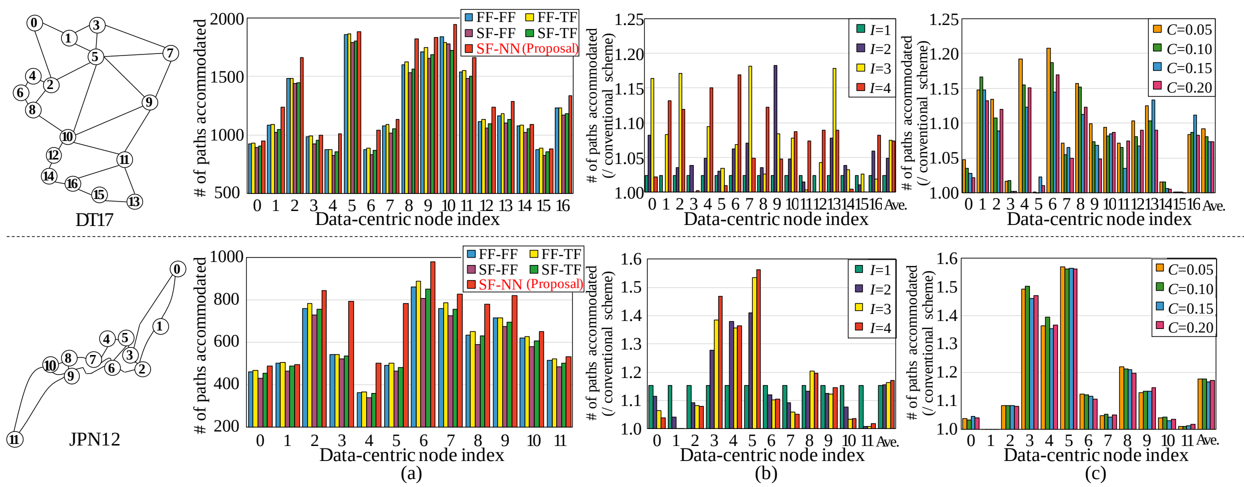

Fig. 3. (a) The number of accommodated paths with I = 4 and C = 0.2, (b),(c) the improvement in the number of accommodated paths with (b) I = 1, 2, 3, 4, C = 0.2, (c) I = 4, C = 0.05, 0.10, 0.15, 0.20; I is the traffic-volume rate relative to the other nodes, C the traffic-churn rate, and Ave. the average of all results in each configuration.

4. Conclusion

In this paper, we proposed an RSA algorithm that suits the dynamically-changing flexible-grid networks expected in the future. The introduction of semi-flexible spectrum assignment successfully eases the computation cost of the ML process. Its effectiveness was analyzed for a wide range of parameters. The number of paths that can be accommodated by a network can increase by 1% to 57%. The scheme was proven to be robust against uncertainty in future traffic conditions including traffic churn and distribution changes.

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5. References

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