IR/AR/MR Service Provisioning in Elastic Optical Networks

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***Abstract*—This work investigates the immediate reservation (IR), advance reservation (AR), malleable reservation (MR) service provisioning in elastic optical networks (EONs). We design request scheduling and/or routing and spectrum allocation (RSA) algorithms for the IR/AR/MR request, respectively. Simulation results show that the proposed IR/AR/MR service provisioning package can reduce request blocking probability effectively.**

***Index Terms*—Elastic optical networks (EONs), Routing and spectrum allocation (RSA), Immediate reservation (IR), Advance reservation (AR), Malleable reservation (MR)**

I. INTRODUCTION

DUE to the enhanced network agility brought by flexible-grid, elastic optical networks (EONs) have attracted intensive research attentions [1]. Besides the enabled technologies, *e.g.*, bandwidth-variable transponders (BV-Ts) and bandwidth-variable wavelength selective switches (BV-WSS'), the flexible control and management of spectrum resources is one of the important research focuses in EONs, which is tightly related to the requests in the optical layer [2]–[4]. To support heterogenous requests, particularly that have diverse QoS parameters such as delay sensitivity and bandwidth requirement, we expect EONs can at least provide three types of services, *i.e.*, immediate reservation (IR), advance reservation (AR), and malleable reservation (MR). Specifically, IR takes care of delay-sensitive requests, and provisions bandwidth immediately upon receiving a request; AR is for the requests that need to reserve bandwidth in advance or are delay-tolerant as long as the service provisioning can be done before a deadline; MR is for the requests that need to accomplish bulk-data transfer timely but do not have rigid requirements on setup delay and transmission bandwidth. In this work, we investigate IR/AR/MR service provisioning in EONs.

The rest of the paper is organized as follows. Section II builds a brief network model for the EONs. Service provisioning algorithms are designed for the IR/AR/MR request in Sections III, IV and V, respectively. Section VI shows the simulation results. Finally, Section VII summarizes the paper.

II. ELASTIC OPTICAL NETWORKS

We model the EON as a direct graph $G(V, E, B)$, where V denotes the node set, E denotes the fiber link set, and B denotes the number of frequency slots (FS') that each fiber can accommodate. We assume there is no spectrum converter in the EON, and hence the spectrum-continuity constraint has to be satisfied when serving a request. Besides, the EON operates in a discrete-time manner, *i.e.*, the time axis is divided into time slots (TS) evenly, and network operations happen at the TS boundaries. To record FS usage on links over time, we define a matrix $[\mathbf{U}]_{|E|\times T}$, where T is the maximum number of look-ahead TS' that the network operator can observe, the element $u_{e,t}$ is a bitmask with a length of B bits to represent the availability of all the FS' on link e in TS t. If the j-th FS on link e is available in TS t, $u_{e,t}[j] = 1$, otherwise $u_{e,t}[j] = 0$.

III. IMMEDIATE RESERVATION

An IR request is modeled with a tuple $IR(s^i, d^i, n^i, \zeta^i, \tau^i)$, where s^i and d^i are the source and destination nodes, n^i is the bandwidth requirement in terms of FS', ζ^i is the arrival TS, and τ^i is the service duration in terms of TS'. To serve an IR request, we need to find an available RSA scheme, *i.e.*, route p_{s^i,d^i} and FS block $[f_s^i, f_e^i]$ on it, where f_s^i and f_e^i are the indices of start FS and end FS, satisfying $f_e^i - f_s^i \geq n^i$. We consider the following factors in the design of IR service provisioning algorithm:

- **Spectrum Efficiency (SE)**: Number of FS' to be assigned for an IR request on the route is calculated as:
$$N_{SE}^i = n^i \cdot hop(p_{s^i,d^i}), \qquad (1)$$
where $hop(p_{s^i,d^i})$ returns the hop count of p_{s^i,d^i}. We prefer to use the route with smaller N_{SE}^i to save more spectrum resources and thus reduce request blocking.
- **Spectrum Misalignment (SM)**: Total number of FS' that are misaligned between each link on the route and its adjacent links in the EON within the scope of assigned FS block is calculated as:
$$N_{SM}^i = \sum_{e \in E^n_{p_{s^i,d^i}}} \sum_{j=f_s^i}^{f_e^i} u_{e,\zeta^i}[j], \qquad (2)$$
where $E^n_{p_{s^i,d^i}}$ is the set of adjacent links for p_{s^i,d^i}. We choose the RSA scheme with smaller N_{SM}^i.
Fig. 1 illustrates an example of spectrum misalignment on adjacent links. Suppose we have an IR request with bandwidth requirement of 2 FS' from *Node* 0 to *Node* 3 in the topology in Fig. 1(a), where the route 0→1→3 is considered. Fig. 1(b) shows the spectrum usage on links, and marks two available FS blocks for the IR request, *i.e.*, FS blocks $[3, 4]$ and $[7, 8]$. Fig. 1(c) shows the adjacent links of *Path* 0→1→3, and plots the misaligned FS' on the links within the two FS blocks. We can see that the number of misaligned FS' is 4 within FS block $[3, 4]$, while it increases to 9 within FS block $[7, 8]$. Therefore, we assign FS block $[3, 4]$ on path 0→1→3 to the request.

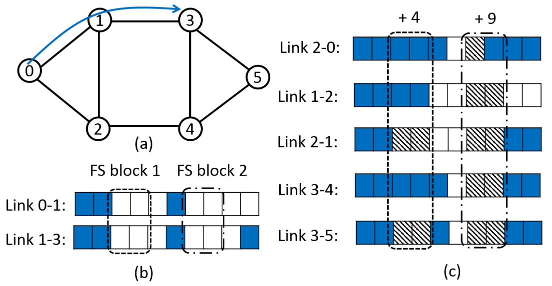

Fig. 1. Example of spectrum misalignment on adjacent links (adapted from [3]).

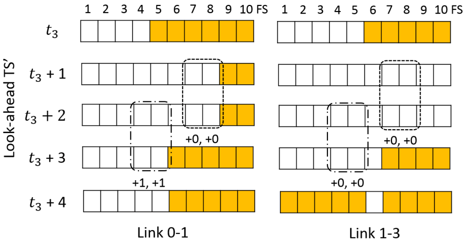

Fig. 2. Example on time fragments (adapted from [3]).

- **Congestion Avoidance (CA)**: Number of FS' that are on the route using highly-congested link(s) is calculated as:

$$N_{CA}^i = \beta \cdot n^i \cdot |E_{p_{s^i,d^i}}^c|, \tag{3}$$

where $E_{p_{s^i,d^i}}^c$ represents the set of highly-congested links on p_{s^i,d^i}, and β is the penalty coefficient. Using this metric, we try to balance traffic on links, and thus reduce service blocking caused by certain highly congested links.

To consider these factors jointly, we put them into a metric for evaluating the value of a RSA scheme, namely spectrum weight, which is calculated as:

$$W_S^i = N_{SE}^i + N_{SM}^i + N_{CA}^i, \tag{4}$$

With precalculated k-shortest path candidates, we try to find available RSA scheme(s) on them, and finally select the one with minimum W_S^i to minimize request blocking probability.

IV. ADVANCE RESERVATION

An AR request is modeled with a tuple $AR(s^a, d^a, n^a, \zeta^a, \delta^a, \tau^a)$, where s^a and d^a are the source and destination nodes, n^a is the bandwidth requirement in term of FS', ζ^a is the earliest service start time, δ^a is the service duration in term of TS', and τ^a is the the latest service end time. To serve an AR request, if $\tau^a > \zeta^a + \delta^a - 1$, we need to 1) schedule it with a valid service time window $[t_s^a, t_e^a]$, where t_s^a and t_e^a are the service start TS and end TS, satisfying $t_e^a = t_s^a + \delta^a - 1$ and $[t_s^a, t_e^a] \in [\zeta^a, \tau^a]$, and 2) find a route p_{s^a,d^a} and reserve an FS block $[f_s^a, f_e^a]$ on it with $f_e^a - f_s^a \geq n^a$. Otherwise, its service time window $[t_s^a, t_e^a]$ is fixed as $[\zeta^a, \tau^a]$, and we only need to find an available RSA scheme $\{p_{s^a,d^a}, [f_s^a, f_e^a]\}$ in it. The flexibility of an AR request can be defined as:

$$\gamma^a = \frac{\tau^a - \zeta^a + 1}{\delta^a} - 1. \tag{5}$$

Note that, a larger flexibility, on one hand, provides the network operator with more freedom on the resource management, on the other hand, increases the degree of AR service satisfaction. Likewise, we consider the following factors in the design of AR service provisioning algorithm:

- **Spectrum Efficiency (SE)**: Number of FS' to be reserved for an AR request on the route during the service time window is calculated as:

$$N_{SE}^a = n^a \cdot hop(p_{s^a,d^a}) \cdot \delta^a. \tag{6}$$

We choose an AR service provisioning scheme with smaller N_{SE}^a to leave more spectrum resources for future requests.

- **Spectrum Misalignment (SM)**: Number of FS' that are misaligned between the links on the route and their adjacent links within the scope of assigned FS block during the service time window is calculated as:

$$N_{SM}^a = \sum_{e \in E_{p_{s^a,d^a}}^n} \sum_{t=t_s^a}^{t_e^a} \sum_{j=f_s^a}^{f_e^a} u_{e,t}[j]. \tag{7}$$

We choose an AR service provisioning scheme with smaller N_{SM}^a.

- **Time Segmenting (TS)**: Number of additional time fragments that are generated due to the reserved FS' on a route during the selected service time window is:

$$N_{TS}^a = \sum_{e \in p_{s^a,d^a}} \sum_{j=f_s^a}^{f_e^a} \phi_{e,j}, \tag{8}$$

where $\phi_{e,j}$ is a binary variable defined as:

$$\phi_{e,j} = \begin{cases} 0, & u_{e,t_s^a-1}[j] \bigoplus u_{e,t_e^a+1}[j] = 1, \\ 1, & otherwise. \end{cases} \tag{9}$$

Considering the fact that 2D spectrum fragmentation increases request blocking probability and reduces spectrum utilization, we try to minimize N_{TS}^a when choosing the scheme for AR. Fig. 2 shows an example on time fragment. Suppose we have an AR request $AR(0, 3, 2, t_3 + 1, 2, t_3 + 3)$ in the topology in Fig. 1(a), and again the route 0→1→3 is considered. The figure plots spectrum usage on the links on the route along the time axis. During each feasible service time window, a suitable FS block has been marked with a rectangle, *i.e.*, FS block $[7, 8]$ during $[t_3 + 1, t_3 + 2]$ and FS block $[4, 5]$ during $[t_3 + 2, t_3 + 3]$. We observe that no time fragment will be introduced by FS block $[7, 8]$ during $[t_3+1, t_3+2]$, since FS block $[7, 8]$ at TS' t_3 and $t_3 + 3$ have already been reserved on both links. However, FS block $[4, 5]$ during $[t_3 + 2, t_3 + 3]$ introduces two time fragments for FS' 4 and 5 on *Link* 0→1. Thus, we prefer to reserve FS block $[7, 8]$ on *Path* 0→1→3 during $[t_3 + 1, t_3 + 2]$ for AR.

To consider these factors jointly, we put them into two metrics for evaluating the value of an AR service provisioning scheme, *i.e.*, 1) spectrum weight as:

$$W_S^a = N_{SE}^a + N_{SM}^a, \tag{10}$$

and 2) time weight that is calculated as:

$$W_T^a = N_{TS}^a. \tag{11}$$

For these two metrics, W_S^a is primary while W_T^a is secondary since we want to emphasize on spectrum savings. Specifically, we try to find AR service provisioning scheme(s) with minimum W_S^a, and if there exist multiple such schemes, we select the one with the minimum W_T^a.

V. MALLEABLE RESERVATION

An MR request is modeled with a tuple $MR(s^m, d^m, \mathcal{F}^m, \zeta^m, \tau^m)$, where s^m and d^m are the source and destination nodes, $\mathcal{F}^m$ is the size of data to be transmitted in terms of the usage of FS over time (*e.g.*, if $\mathcal{F}^m = 6$, we can finish the data transfer using 2 FS over 3 TS), ζ^m is the arrival TS, and τ^m is the TS before when the requested data should be completed. To serve an MR request, we can apply either the adaptive constant bandwidth transmission scheme or the route and bandwidth tunable transmission scheme. The former has lower network operation cost than the latter, though, it cannot utilize spectrum resources so effectively as the latter does. This is because, in the latter scheme, frequent RSA reconfigurations are needed, and thus bring additional network operation cost. Here, we apply the former scheme in the design of MR service provisioning algorithm. Specifically, we need to 1) schedule it with a valid service time window $[t_s^m, t_e^m]$, where t_s^m and t_e^m are the service start TS and end TS, satisfying $[t_s^m, t_e^m] \in [\zeta^m, \tau^m]$, and 2) find a route p_{s^m,d^m} and reserve an FS block $[f_s^m, f_e^m]$ on it, having $(f_e^m - f_s^m + 1) \cdot (t_e^m - t_s^m + 1) \geq \mathcal{F}^m$. Different from AR service provisioning, the length of service time window $[t_s^m, t_e^m]$ and the size of reserved FS block $[f_s^m, f_e^m]$ are alterable for MR. Therefore, we adapt the proposed AR service provisioning algorithm to an adaptive one for MR.

VI. SIMULATION RESULTS

We conduct simulations in the 14-node NSFNET topology, where each fiber can accommodate 358 FS' and each FS has a capacity of 12.5 Gbps. The total traffic load ranges from 150 to 750 Erlangs, and in each case the proportion of IR/AR/MR traffic are 1:1:1. As comparison, we also apply a traditional IR/AR/MR service provisioning package, in which the IR/AR/MR service provisioning algorithms only consider the optimization of spectrum efficiency, while ignoring spectrum fragments. Fig. 3 shows the results on request blocking probability. Compared with the referenced one, the proposed IR/AR/MR package can reduce request blocking probability significantly. Fig. 4 shows the aggregated IR/AR/MR traffic distribution by the proposed package. As the traffic load increases, the served IR traffic becomes less while the served AR/MR traffic become more. This is because AR/MR requests have more service flexibility than the IR requests, and thus can get a higher degree of service satisfaction especially when there is resource competition.

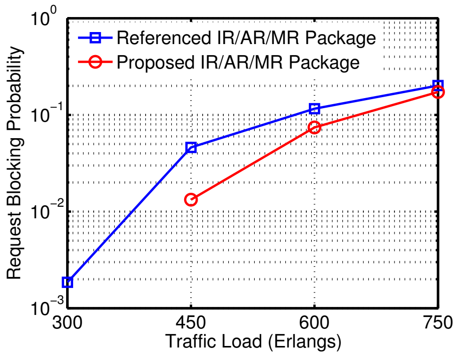

Fig. 3. Results comparison on request blocking probability.

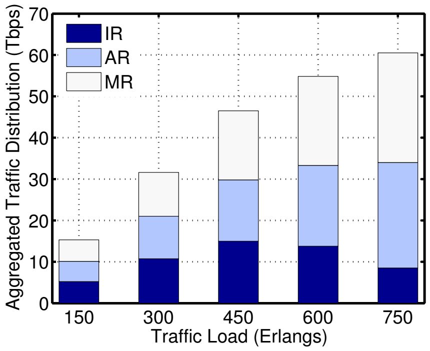

Fig. 4. Distribution of aggregated IR/AR/MR traffic.

VII. CONCLUSION

This paper proposed three request scheduling and/or RSA algorithms for the IR/AR/MR requests in EONs. Simulation results showed that the proposed IR/AR/MR service provisioning package could reduce request blocking probability effectively.

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