Dynamic Multi-Path Service Provisioning under Differential Delay Constraint in Elastic Optical Networks

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***Abstract*—Optical orthogonal frequency-division multiplexing (O-OFDM) technology has the elastic feature of allocating spectrum resources based on subcarrier slots with bandwidths at a few GHz or even narrower. This feature enables us to utilize link capacity more efficiently by splitting a connection's traffic over multiple routing paths. In this paper, we propose a novel dynamic multi-path provisioning algorithm for O-OFDM based elastic optical networks. The algorithm tries to set up dynamic connections with single-path routing in a best-effort manner. When a connection cannot be served with a single routing path, the algorithm uses an auxiliary-graph based approach to calculate a multi-path provisioning scheme based on two parameters, *i.e.*, the differential delay upper-bound and the bandwidth allocation granularity. Simulation results indicate that compared with several existing single-path provisioning algorithms, the proposed algorithm provides lower bandwidth blocking probability and achieves $10-18\%$ improvement on average network throughput.**

***Index Terms*—Optical orthogonal frequency-division multiplexing (O-OFDM), routing and spectrum assignment (RSA), multi-path provisioning algorithm, differential delay constraint.**

I. Introduction

RECENTLY, optical orthogonal frequency-division multiplexing (O-OFDM) technology [1], [2] has attracted intensive research interests due to the reason that elastic optical networks can be constructed based on it. Previous works have studied a few network planning and provisioning approaches [3]–[7] to take the advantages of its sub-wavelength bandwidth allocation granularity. These investigations suggested that the flexible-grid O-OFDM networks can achieve better network performance than those based on fixed-grid wavelength-division multiplexing (WDM). However, most of the previous works on O-OFDM networks only considered single-path routing for network planning and provisioning. It is known that single-path routing can cause unbalanced traffic distribution and make networks deviate from their optimal operation points [8]. Moreover, for dynamic provisioning, especially when the traffic load is high, we may have difficulty to find a single routing path that can satisfy the total capacity of a request. Then, the blocking probability can be high.

Multi-path routing schemes have already demonstrated improved network performance in WDM networks [9], SONET/SDH networks [10], [11], and video distribution networks [12], [13]. Meanwhile, it has been a consensus that they need to address the differential delay between routing paths properly, due to the limited buffer sizes on end nodes and/or the QoS constraints from network applications [12], [14]. The elastic nature of O-OFDM enables us to split a connection's traffic over multiple routing paths without causing significant bandwidth waste. However, since we have to consider the spectrum continuity and spectrum non-overlapping constraints in routing and spectrum assignment (RSA), dynamic multi-path provisioning in O-OFDM networks can be intrinsically more complicated than those in WDM or SONET/SDN networks. In this paper, we propose a novel dynamic multi-path service provisioning algorithm that is specifically designed for O-OFDM networks and considers the differential delay constraint. The proposed algorithm tries to set up dynamic connections with single-path routing in a best-effort manner. If this cannot be done, it uses an auxiliary-graph based approach to calculate a multi-path provisioning scheme based on two parameters, *i.e.*, the differential delay upper-bound and the bandwidth allocation granularity. To the best of our knowledge, this is the first proposal to address dynamic multi-path provisioning under the differential delay constraint in elastic optical networks. Simulation results demonstrate that the multi-path scheme outperforms two single-path ones by providing lower bandwidth blocking probability and achieves $10-18\%$ improvement on average network throughput.

II. Elastic Multi-Path Provisioning Algorithm

We consider the elastic optical network as a weighted graph $G(V,E,B,D)$, where V is the node set, E is the fiber link set, and B and D represent the available bandwidths and delays of links $e\in E$, respectively. For a connection request $L_{s,d}$ from node s destined to node d, we assume $\mathbb{R}_{s,d}$ is the set of feasible routing paths. Then, the differential delay of $\mathbb{R}_{s,d}$ is defined as the delay difference between the longest and shortest paths in it. Normally, in multi-path provisioning, we can tolerate the differential delay until it reaches an upper-bound. We denote this upper-bound as J_{max}. To avoid splitting a request over too many routing paths, we define a bandwidth allocation granularity as g subcarrier slots. Specifically, when the multi-path scheme is used, the minimum number of contiguous slots we can allocate on a path is g. The elastic multi-path provisioning algorithm has three steps:

1) For each s-d pair in G, we calculate all feasible routing paths during network initialization, using a breadth-first path search (BFPS) algorithm [15]. When provisioning a request $L_{s,d}$, we find the maximum available aggregated bandwidth (in number of slots) from s to d by converting $G(V,E,B,D)$ into a max-flow graph $G^{'}(V^{'},E^{'},B^{'},D^{'})$ under the spectrum continuity constraint. Specifically, the max-flow graph $G^{'}$ is constructed by aggregating the available slots on all feasible

Manuscript received June 18, 2012. The associate editor coordinating the review of this letter and approving it for publication was J. Wang.

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Digital Object Identifier 10.1109/LCOMM.2012.120612.121343

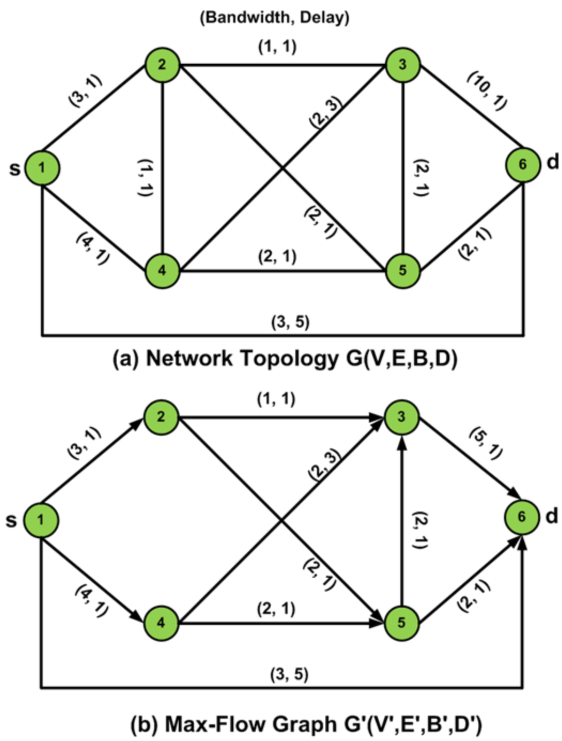

Fig. 1. Transform (a) the network topology into (b) a max-flow graph.

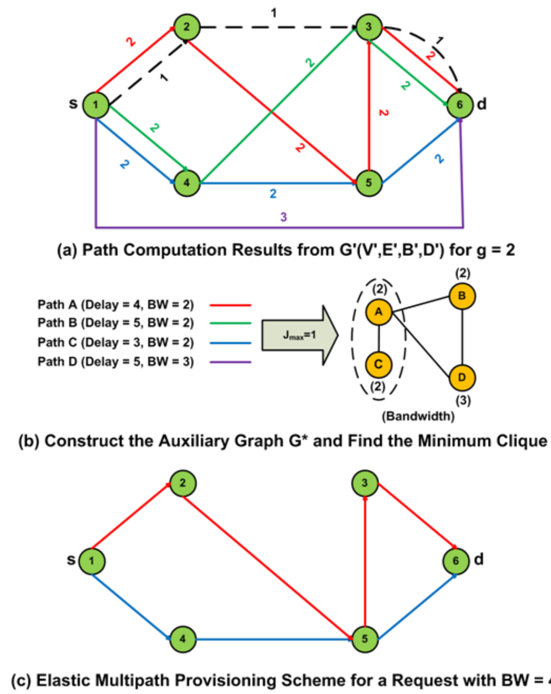

Fig. 2. (a) Path computation based on the max-flow graph, (b) Construct the auxiliary graph G^* based on g and J_{max}, and (c) Elastic multiplath provisioing scheme for a $L_{1,6}$ for 4 slots.

paths from s to d. The deliverable bandwidth from s to d is then upper-bounded by the bandwidth of the max-flow. $L_{s,d}$ is blocked immediately, if we find its bandwidth requirement larger than this deliverable bandwidth.

2) The path candidates are calculated in iterations. In each iteration, a shortest path is selected from the path set $\mathbb{R}_{s,d}$. We then obtain the available contiguous slots along the selected path, and remove them from $G^{'}$. We validate the path by making sure that the largest available block of contiguous slots over it has a size $\geq g$. Otherwise, the path is dropped. If the path is a valid candidate, one or more nodes are inserted into the auxiliary graph G^* in a way that each node represents an available block of contiguous slots over the path. We then connect two nodes in G^*, if the differential delay between the paths represented by them is $\leq J_{max}$.

3) A clique of G^* is a complete sub-graph in it, *i.e.*, sets of nodes that any two of them are connected. The provisioning algorithm searches for a clique in G^* that can support $L_{s,d}$ with the minimum number of nodes (*i.e.*, routing paths). If the clique exists, $L_{s,d}$ is provisioned over the paths represented by it; otherwise, it is blocked.

Figs. 1 and 2 show an intuitive example of the elastic multi-path provisioning algorithm. When the request $L_{1,6}$ for 4 slots arrives, the network status is shown in Fig. 1(a). Fig. 1(b) shows the max-flow graph $G^{'}$ obtained from the current network status. The upper-bound of available slots from node 1 to node 6 is 10. However, since none of the single paths can support 4 slots, the request would be blocked if there is no multi-path provisioning. In order to achieve multiplath provisioning, we calculate the routing paths from $G^{'}$ as shown in Fig. 2(a). If we set the bandwidth allocation granularity $g = 2$, then the solid lines represent the valid routing paths, while the dash lines are for the path that needs to be dropped. The auxiliary graph G^* is constructed as shown in Fig. 2(b), for path selection under the differential delay constraint $J_{max} = 1$. We finally choose Paths A and C to serve $L_{1,6}$.

III. Performance Evaluations

We evaluate the performance of the proposed elastic multi-path provisioning algorithm with simulations using the 14-node NSFNET topology. We assume that the bandwidth of a slot is 12.5 GHz, which is a typical value in O-OFDM networks [4], [5]. If the network is deployed in the C-Band, each fiber link has ∼4.475 THz bandwidth to allocate, which corresponds to 358 subcarrier slots. The bandwidths of the connections are uniformly distributed within $1 - 16$ slots, and their s-d pairs are randomly chosen. In conjunction with multi-path routing, we use a first-fit spectrum assignment scheme and hence the proposed algorithm can be named as MP-FFSA. We set the upper-bound of the differential delay J_{max} as 15 ms (*i.e.*, 3000 km distance difference). In the dynamic provisioning, we generate requests according to a Poisson process with an average rate of λ requests per time unit, and the duration of each request follows the negative exponential distribution with an average value of $\frac{1}{\mu}$ time units. Hence, the traffic load can be quantified with $\frac{\lambda}{\mu}$ in Erlangs. We also implement two single-path dynamic provisioning algorithms, the shortest path and first-fit spectrum assignment (SP-FFSA) [3], and the K-shortest paths and balanced load spectrum assignment (KSP-BLSA) [15]. They are simulated as the reference algorithms.

TABLE I
AVERAGE NETWORK THROUGHPUT (TB/S)

Traffic Load (Erlangs)	SP-FFSA	KSP-BLSA	MP-FFSA				
			$g=1$	$g=2$	$g=3$	$g=4$	$g=5$
300	31.85	32.94	33.07	33.07	33.07	33.07	33.07
400	37.71	39.07	40.84	40.84	40.84	40.84	40.84
500	44.07	44.14	52.05	51.98	51.30	50.60	50.19
600	48.26	48.89	59.60	58.06	56.94	55.66	54.73
700	53.99	53.00	67.09	64.61	63.18	61.29	60.62
800	59.79	59.61	71.97	69.44	67.26	65.83	64.55
900	60.89	59.88	74.54	71.38	69.10	67.04	65.99
1000	64.88	62.37	78.30	75.47	73.14	71.54	70.35

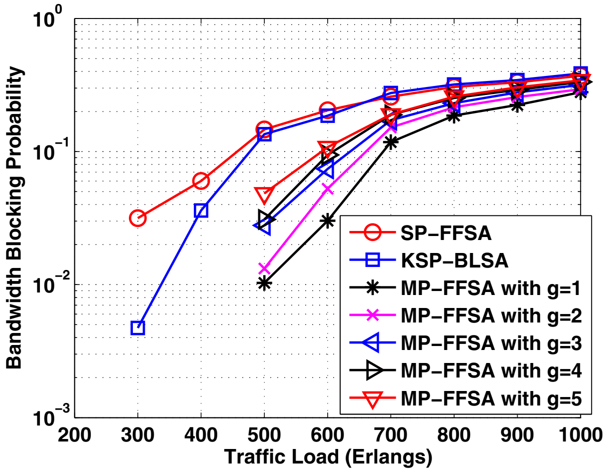

Fig. 3. Bandwidth blocking probability.

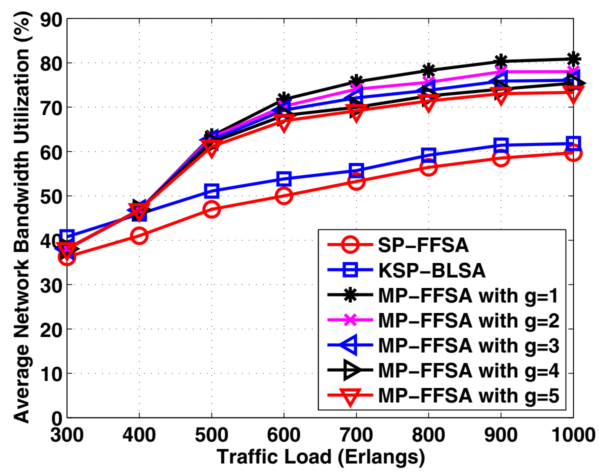

Fig. 4. Average network bandwidth utilization.

Fig. 3 shows the simulation results on bandwidth blocking probability (BBP). Here, we define BBP as the ratio of blocked bandwidth versus total requested bandwidth. We test the proposed MP-FFSA algorithm with bandwidth allocation granularity $g = 1$ to 5 slot(s). We observe that the MP-FFSA algorithm outperforms single-path provisioning algorithms, by providing smaller BBPs. The BBP of MP-FFSA increases when we increase g. This is because that when g gets bigger, it will be more difficult for the MP-FFSA to find an available path that can accommodate g contiguous slots. Fig. 4 shows the results on average network bandwidth utilization. The SP-FFSA algorithm provides the smallest network bandwidth utilization. Compared with KSP-BLSA, MP-FFSA achieves $15-23\%$ improvement on average network bandwidth utilization for different g, when the traffic load is 1000 Erlangs. Table I shows the results on average network throughput for different traffic loads. When the traffic load is low (*i.e.*, 300 Erlangs), the results from MP-FFSA do not have significant difference from those from SP-FFSA and KSP-BLSA. When the traffic load keeps increasing, MP-FFSA can achieve $10 - 18\%$ improvement on average network throughput.

Fig. 5 illustrates the distribution of the number of paths for provisioned connection requests using MP-FFSA with $g = 2$. When the traffic load is lower than 400 Erlangs, all requests are served with a single routing path. From 400 to 1000 Erlangs, the percentage of multi-path provisioned connections increases gradually. This due to the reason that when the traffic load is higher, the links become more crowded and it is more difficult for the provisioning algorithm to find a single path that can satisfy the total bandwidth of a request. However, even when the traffic load is as high as 1000 Erlangs, the majority of the requests ($>62\%$) are still served with a single path due to the effectiveness of the auxiliary-graph based approach. Fig. 6 plots the distribution of path-distance difference of the requests that are served with multiple paths in MP-FFSA with $g = 2$, for traffic loads $400 - 1000$ Erlangs. Notice that in our multi-path provisioning scheme, a connection can be served with a single routing path, but using a few non-contiguous slot blocks. We consider this as a multi-path case since more than one sets of O-OFDM transponders are required. The results in Fig. 6 suggest that the MP-FFSA algorithm achieves 0 differential delay for $\sim 87\%$ of the multi-path provisioned requests and the path-distance difference is well-controlled within 3000 km (*i.e.*, 15 ms differential delay).

Since it needs to manipulate an increased number of network elements during connection setting up and tearing down, the multi-path provisioning scheme can introduce control overhead and make the connection setup time longer. Therefore, there is a tradeoff between the performance improvement and control overhead. As we design the multi-path provisioning scheme with an adjustable bandwidth allocation granularity g, it will be our next step to investigate the impact of g on this tradeoff.

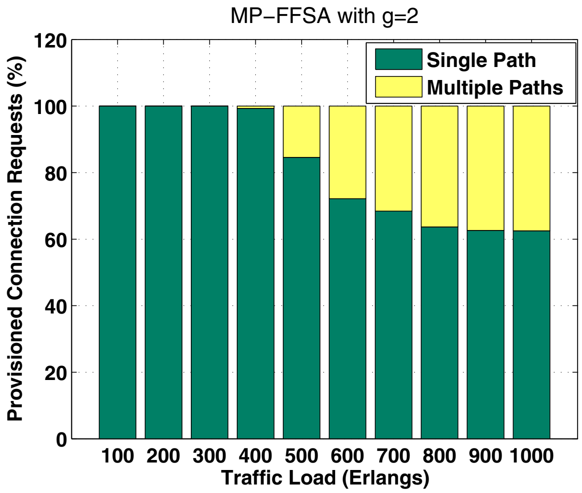

Fig. 5. Distribution of single-path and multi-path served requests in MP-FFSA with $g = 2$.

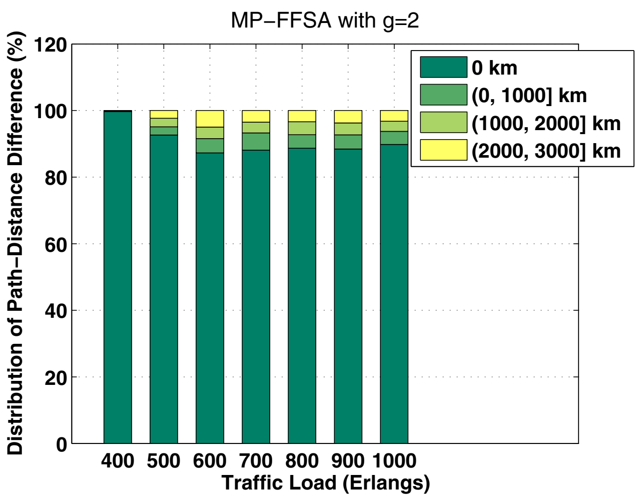

Fig. 6. Distribution of the path-distance differences of requests served with multiple paths in MP-FFSA with $g = 2$.

IV. CONCLUSION

We proposed a novel dynamic multi-path provisioning algorithm for elastic optical networks based on O-OFDM. The algorithm tried to set up dynamic connections with single-path routing in a best-effort manner. When a connection could not be served with a single routing path, the algorithm used an auxiliary-graph based approach to calculate a multi-path provisioning scheme based on the differential delay upper-bound and the bandwidth allocation granularity. Simulation results demonstrated that compared with two existing single-path schemes, the proposed algorithm effectively reduced bandwidth blocking probability and achieved $10 - 18\%$ improvement on average network throughput, in dynamic provisioning. In the simulation scenario with the highest traffic load (1000 Erlangs) and bandwidth allocation granularity $g = 2$, $\sim$62% of the requests were still served with a single routing path. Among the 38% multi-path served requests, $\sim$87% were served with paths that had 0 differential delay and the differential delays of the rest were well-controlled within the preset threshold.

ACKNOWLEDGMENTS

This work was supported in part by the Program for New Century Excellent Talents in University (NCET) under Project NCET-11-0884, and the Natural Science Foundation of Anhui Province under Project 1208085MF88.

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