Abstract—Next generation optical networks will be required to provide increased data throughput on a greater number of optical channel and will also have to facilitate network flexibility in order to adapt to dynamic traffic patterns. Recently optical orthogonal frequency division multiplexing (O-OFDM) has been considered as a promising technology for future high speed optical transmission. The elastic nature of optical-OFDM imposes sophisticated network planning and provisioning procedure for efficient and robust operation. Empowered by optical orthogonal frequency division multiplexing methodology, flexible online service provisioning can be realized with dynamic routing, modulation and spectrum assignment (RMSA), which is used for network control and management. This paper incorporates dynamic RMSA with hybrid single/-multi-path routing (HSMR) scheme. We investigate two types of HSMR scheme, namely HSMR using online path computations (HSMR-OPC) and HSMR using fixed path sets (HSMR-FPS). The simulation results have demonstrated that the proposed HSMR schemes can effectively reduce the bandwidth blocking probability (BBP) of dynamic RMSA, as compared to optical WDM network. Simulation results suggest that HSMR-OPC can achieve the lowest BBP among all HSMR schemes. The HSMR-OPC optimizes routing paths for each request on the fly with consideration of both bandwidth utilizations and lengths of links. Simulation result also indicate that the HSMR-FPS scheme that use the largest slots-over-square-of-hops first path selection policy obtain the lowest BBP among all HSMR-FPS schemes.

Index Terms—Bandwidth blocking probability (BBP), Hybrid single/-multi-path routing (HSMR), Optical orthogonal frequency division multiplexing (OOFDM), Routing, modulation and spectrum assignment (RMSA).

I. INTRODUCTION

Over the past decade, Internet traffic has been growing at an annual rate of more than 30%, and the consequent bandwidth (BW) demands stimulated research and development for highly flexible and scalable networking technologies. Traditional optical transport networks are built based on point-to-point wavelength division multiplexing (WDM) transmission systems, in a circuit-switching manner. Since the bandwidth allocation granularity of WDM technology is usually coarse, i.e. 50 or 100 GHz per channel, these optical circuit-switching networks have been considered as with rigid infrastructures that only have minimum intelligence and flexibility in optical layer. Recent research advance has been experimentally demonstrated transmission of 20 Tb/s signals on a single fiber with the dense wavelength division multiplexing (DWDM) technology [1].

However, due to the coarse granularity of DWDM network infrastructure [2] has been considered rigid with limited elasticity and flexibility in the optical layer. To support highly dynamic IP data traffic, repeated optical-to-electrical-to-optical (O/E/O) conversions are used to forward data to electrical routers for packet-switching. However, it is well known that high-speed O/E/O conversions associate with relatively high equipment cost and energy consumption [3]. To this end, the skyrocketing capital expenditures (CAPEX) and operational expenditures, and project the inevitable trend of developing more elastic, agile and intelligent optical technologies. To this end, it is highly desirable to develop networking technology that provides subwavelength granularity in the optical layer.

A. Optical Orthogonal Frequency division Multiplexing (O-OFDM)

Recent advances in optical orthogonal frequency division multiplexing (O-OFDM) technology have demonstrated efficient and elastic bandwidth allocation in the optical layer [4], [5]. Working in a multi-carrier scenario, O-OFDM supports ultra-high speed data transmission by grooming the capacities of several low-speed subcarrier channels. Due to the fact that the subcarriers are orthogonal in the frequency domain, their spectra can overlap with each other for high spectral efficiency. Compared to single-carrier WDM, O-OFDM provides finer bandwidth transponder [6] can adjust spectral resource and assign just-enough subcarrier slots to serve a lightpath request.
In elastic optical networks (EON), the fundamental problem of network planning and provisioning is routing and spectrum assignment (RSA). When RSA becomes impairment aware, an O-OFDM transponder can make the modulation level of its subcarrier slots to be adaptive to the quality of transmission of a lightpath [7], [8]. When the lightpath requests are known a prior, offline planning of O-OFDM networks with RMSS under the spectrum continuity is known as nonpolynomial complete [9], several integer linear programming (ILP) models were formulated and solved for offline RSA, and heuristic based on shortest path routing and simulated annealing optimization was proposed to reduce the computation complexity.

An RSA heuristic that combined shortest path routing and first-fit spectrum assignment was discussed in [10]. Jinno et al [11] proposed a BW efficient RSA, which examined K-shortest routing paths for each request and then chose the one with the lowest available contiguous slots. Wang et al [12] formulated an ILP model for offline RSA and designed two heuristics, K-shortest path routing and balanced-load spectrum assignments and shortest path routing and maximum spectrum reuse assignments.

Online provisioning of O-OFDM networks considers how to serve time-variant lightpath requests with dynamic RSA. By leveraging the generalized multiprotocol label switching signaling mechanism, a distributed dynamic RSA was proposed in [13], which chose the least congested routing path and performed first-fit spectrum assignments. [14] Developed a dynamic RSA that used a metric to quantify the consecutiveness of available slots among relevant fibers. The investigation in [15] considered spectrum defragmentation during online provisioning with dynamic RSA.

![Block diagram of Optical Orthogonal Frequency Division Multiplexing](image)

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**B. Service Provisioning With Multipath Routing**

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 [16]. 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. It is known that multipath routing provides increased throughput and utilizes the network resources more efficiently. Researchers have previously considered including multipath routing supports in SONET/SDH transport systems [17]-[19]. Multipath routing is also explicitly supported by several standardized routing protocols such as the open shortest path first [20] and the routing information protocol [21].

The elastic nature of O-OFDM enables us to split a connection’s traffic over multiple routing paths without causing significant bandwidth waste [22]. However, since we have to consider the spectrum continuity and spectrum non-overlapping constraints in routing and spectrum assignment (RSA), dynamic multipath provisioning in O-OFDM networks can be intrinsically more complicated than those in WDM networks. However, since this approach still restricted all subflows of a request to be routed over the same path, it may not fully explore the benefits of multipath provisioning. In order to support traffic-splitting and multipath routing in O-OFDM networks, each switching node requires a wavelength-selective switch (WSS) that can add/drop subcarrier channels using relatively low BW granularity.

**C. Our Contribution**

In this paper, we propose several dynamic service provision algorithms that incorporate a hybrid single-multi-path routing (HSMR) scheme. This is the attempt to consider dynamic RSA based on both online path computation and offline path computation with various path selection policies for multipath provisioning in O-OFDM networks. Notice that for multipath service provisioning, the differential delay constraint (DDC) between the routing paths can lead to the requirement for additional buffers on the end nodes [25]. We expect that the issue can be resolved with either the split-spectrum approach that restricts all subflows of a request to be routed over the same path [22] or a multipath provisioning approach that considers the differential delay constraint.
II. PROBLEM FORMULATION OF SERVICE PROVISIONING USING DYNAMIC RMSA WITH HSMR

With a physical network topology as $G(V,E,B,D)$, where $V$ is the node set, $E$ is the fiber link set, each fiber link can accommodate $B$ frequency slots at most, and $E \subseteq E$. We assume that the bandwidth of each subcarrier slot is unique as $B_{\text{slot}}$ GHz. The capacity of a slot is $C_{\text{slot}}$, where $M$ is the modulation level in terms of bits per symbol, and $C_{\text{slot}}$ denotes the capacity of a slot when the modulation is BPSK ($M=1$) and is a function of $B_{\text{slot}}$ [9]. In this work, we assume that $M$ can be 1, 2, 3 and 4 for BPSK, QPSK, 8-QAM and 16-QAM respectively. For a lightpath request $LR(s,d,C,\Delta t)$ that is from node $s$ to $d$ for a capacity of $C$ with a duration of $\Delta t$, the dynamic RMSA provisioning algorithm first needs to determine a routing path $R_{s,d}(i)$ to serve the request, where $i$ is the index of each routing path.

When the transmission distance of the routing path is known, we derive the modulation level $M$ the path can support. Specifically, we assume that each modulation $M$ can support a maximum transmission distance based on the receiver sensitivities and when the distance permits, we always assign the highest modulation level to the request for high spectral efficiency. The last step of dynamic RMSA is the spectrum assignment to finalize the allocations of contiguous slots along the fiber links on $R_{s,d}(i)$. The objective of service provisioning is to minimize BBP or to maximize network throughput.

**Definition 1 (BW allocation granularity):** To avoid a request $LR$ from being split over too many paths, we define a BW allocation granularity as $g$ slots. Specifically, when $LR$ is provisioned over more than one routing paths, the minimum size of the slot blocks we can allocate on each path is $g$. Note that increasing $g$ discourages multipath provisioning schemes, and will eventually lead to a single-path-only scenario when $g$ is comparable to the largest size of the requests.

**Definition 2 (Bandwidth blocking probability):** BBP is defined as the ratio of blocked connection BW versus total request BW. BBP is a commonly used metric for assessing the performance of service provisioning algorithms.

**Definition 3 (BW fragmentation ratio):** BW fragmentation is another interesting factor which is similar to the file system fragmentation in computer storage, usually refers to the existing of nonaligned, isolate and small-sized slot blocks in the spectrum of EONs.

III. DYNAMIC RMSA ALGORITHM WITH HSMR USING ONLINE PATH COMPUTATION

We first investigate a dynamic RMSA-HSMR algorithm that considers link spectrum usage on the fly with an online path computation. Specifically, we convert $G(V,E,B,D)$ to a virtual topology $G'(V,E,D')$ based on link spectrum usage, where $V$ and $E$ are the same as those in $G$, but each link weight $d_{e}$ in set $D'$.
Figure 3 shows the detailed procedure in implementing the proposed algorithm, and we calculate the routing path set for the path selection of each request using network status on the fly.

### TABLE I. Parameter Description

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>V</td>
<td>Node set</td>
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<tr>
<td>E</td>
<td>Fiber link set</td>
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<tr>
<td>B</td>
<td>Frequency slot</td>
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<td>D</td>
<td>Length of fiber</td>
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<tr>
<td>S</td>
<td>Source</td>
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<td>D</td>
<td>Destination</td>
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<tr>
<td>C</td>
<td>Requested capacity</td>
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<tr>
<td>C_i</td>
<td>Capacity of i-th routing path</td>
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<tr>
<td>d_i</td>
<td>Link weight</td>
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<tr>
<td>g</td>
<td>Granularity</td>
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</tbody>
</table>

### IV. DYNAMIC RMSA ALGORITHM WITH HSMR USING FIXED PATH SETS

The major drawback of online path computation is the high computation complexity, as we need to reconstruct the virtual topology $G$ for each request and to perform path computation on the fly. Dynamic RMSA with HSMR can also be realized using fixed path sets, where the path-set containing K-shortest routing paths for each s—d pair in $G$ are precomputed before operating the network. Hence, the overhead from path computation can be effectively reduced. Figure 4 shows the detailed procedure in implementing the proposed algorithm. In provisioning a lightpath request $LR(s,d,C)$, we sort the paths in the path set of $s—d$ based on a path selection policy and then process the paths one by one.

We evaluate the following path-selection policies:

**Shortest path first (SPF):** We select the routing path candidates in the ascending order based on the total transmission distance of the routing path.

$$dist(R_{s,d,i}) = \sum_{e} d_e$$

**Most slots first (MSF):** We select the paths in the descending order based on the total available slots on each of them.

**Largest slots-over-hops first (LSoHF):** We select the paths in the descending order based on the metric

$$slh(R_{s,d,i}) = \frac{bw(R_{s,d,i})}{\text{hop}(R_{s,d,i})}$$

**Largest slots-over-square-of-hops first (LSoSHF):** We order the paths in the descending order based on the metric

$$slsh(R_{s,d,i}) = \frac{bw(R_{s,d,i})}{\sqrt{\text{hop}(R_{s,d,i})}}$$

### V. PERFORMANCE EVALUATION

We evaluate the performance of the proposed dynamic RMSA algorithm with HSMR in 14-node NSFNET network topology which we used in simulation for performance evaluation of the proposed service provisioning algorithms. We set the bandwidth of a subcarrier slot as 12.5 GHz, and assume that the transmission reach for BPSK, QPSK, 8-QAM and 16-QAM signals in it as 9600 km, 4800 km, 2400 km, and
1200 km, respectively. We set $B=300$ as the number of slots on each fiber. The connection requests are generated using the Poisson traffic model. The capacity $C$ of each request is randomly chosen with 10-200 Gb/s. Note that we use the first-fit spectrum assignment scheme for the proposed HSMR algorithm in the simulation.

The dynamic provisioning, we generate requests according to a Poisson process with an average rate of $\lambda$ requests per time unit, and the duration of each request follows the negative exponential distribution with an average value of $1/\mu$ time units. Hence, the traffic load can be quantified with $\lambda \mu$ in Erlangs. The Result also suggests that the dynamic RMSA with HSMR using online path computations (HSMR-OPC) achieves the lowest BBP among all hybrid single-/multi-path routing schemes. This is attributed to the fact that hybrid single-/multi-path routing-OPC optimize routing paths for each request on the fly with considerations of the BW utilizations and lengths of links. Among the hybrid single-/multi-path routing schemes that use fixed path sets, HSMR-FPS-SLoSHF path selection policies consider the balance between path length and link utilization, and hence achieve better BBP performance. Its BBP performance is just slightly worse than that of HSMR-OPC. Figure 6, 7 show the simulation results on BBP in NSFNET topology.

**REFERENCES**


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