Dynamic Survivable Multipath Routing and Spectrum Allocation in OFDM-Based Flexible Optical Networks

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***Abstract*—Compared to traditional wavelength division multiplexing (WDM) networks, orthogonal frequency division multiplexing (OFDM)-based flexible optical networks provide better spectral efficiency due to their flexible bandwidth allocation capability and fine granularity. Survivability is a crucial issue in OFDM-based flexible optical networks. Recently we proposed a new survivable multipath provisioning scheme (MPP) that efficiently supports demands with flexible protection requirement in OFDM-based optical networks and studied the static survivable multipath routing and spectrum allocation (SM-RSA) problem, which aims to accommodate a given set of demands with minimum utilized spectrum. We have showed that the MPP scheme achieves higher spectral efficiency than the traditional single-path provisioning (SPP) scheme. In this paper, we study the dynamic SM-RSA problem, which selects multiple routes and allocates spectrum on these routes for a given demand as it arrives at the network. We develop an integer linear programming (ILP) model as well as a heuristic algorithm for the dynamic SM-RSA problem. We conduct simulations to study the advantage of MPP over SPP for the dynamic traffic scenario in terms of blocking performance and fairness. We also compare the performance of the MPP heuristic algorithm and the ILP model.**

***Index Terms*—Dynamic routing and spectrum allocation; Flexible optical networks; Multipath provisioning; Optical OFDM; Protection.**

I. Introduction

In conventional wavelength division multiplexing (WDM) optical networks, a connection is supported by a wavelength channel occupying a 50 GHz spectrum. This rigid and coarse granularity leads to waste of spectrum when the traffic between the end nodes is less than the capacity of a wavelength channel. To address this issue, optical networks capable of flexible bandwidth allocation with fine granularity are needed. Orthogonal frequency division multiplexing (OFDM) is a promising modulation technology for optical communications because of its good spectral efficiency, flexibility, and tolerance to impairments [1,2]. In optical OFDM, a data stream is split into multiple lower rate data streams, each modulated onto a separate subcarrier. By allocating an appropriate number of subcarriers, optical OFDM can use just enough bandwidth to serve a connection request. A novel OFDM-based optical transport network architecture called a spectrum-sliced elastic optical path network (SLICE) is proposed in [3]. The SLICE network can efficiently accommodate subwavelength and superwavelength traffic by allocating just enough spectral resource to an end-to-end optical path according to the user demand. The performance superiority of OFDM-based flexible optical networks over conventional WDM optical networks has been demonstrated in [4–7].

An important problem in the design and operation of OFDM-based flexible optical networks is the routing and spectrum allocation (RSA) problem. The RSA problem for static demands is studied in [8,9]. In [10,11], dynamic RSA algorithms are proposed to efficiently accommodate connection requests as they arrive at the network. In [12], the authors propose a split spectrum approach that splits a bulky demand into multiple spectrum channels, all of which are routed over the same path. This approach relaxes the constraint of transmission impairment over long distance and also makes more efficient use of discontinued spectrum fragments. A similar approach called lightpath fragmentation is proposed in [13]. A dynamic multipath provisioning (MPP) algorithm with differential delay constraints for OFDM-based elastic optical networks is proposed in [14]. Here a demand is split over multiple routing paths. In [15], the authors propose several dynamic routing, modulation, and spectrum assignment algorithms in elastic optical networks with hybrid single-/multipath routing. These algorithms achieve lower bandwidth blocking probability (BBP) than the conventional single-path routing and the split spectrum approaches.

Survivability is a crucial requirement in optical transport networks. The authors in [16] propose a heuristic algorithm for survivable flexible WDM network design. In [17], two backup sharing policies for OFDM-based optical networks are proposed. A single-path provisioning (SPP) multipath recovery scheme in flexgrid optical networks is presented in [18]. Recently, the authors in [19] have proposed a survivable MPP scheme for OFDM-based flexible optical networks that can support full and partial protection with higher efficiency than the conventional SPP scheme. In the survivable MPP scheme, a demand is routed over multiple link-disjoint paths and subcarriers are allocated on these paths to satisfy the bandwidth requirement and the protection requirement of the demand. The static

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survivable multipath routing and spectrum allocation (SM-RSA) problem for accommodating a given set of demands has been studied in [19].

In this paper, we study the SM-RSA problem for dynamic traffic demands. When a demand arrives at the network, a dynamic SM-RSA algorithm is needed to compute the routes for the demand and allocate subcarriers on the routes to accommodate the demand. We develop an integer linear programming (ILP) model as well as an efficient heuristic algorithm for the dynamic SM-RSA problem. We conduct simulations to demonstrate the advantage of MPP over SPP in the dynamic traffic scenario and evaluate the performance of the ILP and heuristic algorithms.

The rest of the paper is organized as follows. In Section II we define the dynamic SM-RSA problem. In Section III we develop an ILP model for the dynamic SM-RSA problem. A heuristic algorithm for the dynamic SM-RSA problem is given in Section IV. In Section V we present the numerical results. Finally, we conclude the paper in Section VI.

II. Dynamic Survivable Multipath Routing and Spectrum Allocation Problem

In OFDM-based flexible optical networks, the frequency spectrum is divided into a number of subcarriers with equal frequency. We assume a connection request has a bandwidth requirement and a protection requirement. Specifically, a request is represented by $r = \langle s, d, B, q \rangle$, where s and d are the source and destination nodes, B is the bandwidth requirement in terms of the number of subcarriers requested, and q $(0 \le q \le 1)$ is the protection requirement indicating qB bandwidth must be available after any single link failure. Note that $q = 0$ indicates no protection, $q = 1$ indicates full protection, and $0 < q < 1$ indicates partial protection.

Given a connection request $r = \langle s, d, B, q \rangle$, the dynamic SM-RSA problem is to find $N \ge 2$ link-disjoint paths between s and d, and allocate subcarriers on each of the N paths such that the total allocated subcarriers on the N paths is at least B (the bandwidth requirement), and the total allocated subcarriers on any group of $N-1$ paths is at least qB (the protection requirement). To achieve low blocking, we seek a solution that minimizes the total number of subcarriers allocated to the demand, which equals $\sum_{i \in [1,N]} A_i \times L_i$. Here A_i is the number of subcarriers allocated on path i, and L_i is the length of path i in hops.

In addition to satisfying the bandwidth and protection requirements, the following constraints must be satisfied when accommodating a demand:

- *Spectrum contiguity constraint:* A set of contiguous subcarriers must be allocated on a spectrum path.
- *Nonoverlapping spectrum constraint:* A subcarrier on a link can be allocated to at most one spectrum path routed over the link.
- *Guard subcarrier constraint:* When two adjacent spectrum paths share a link, they must be separated by G guard subcarriers.

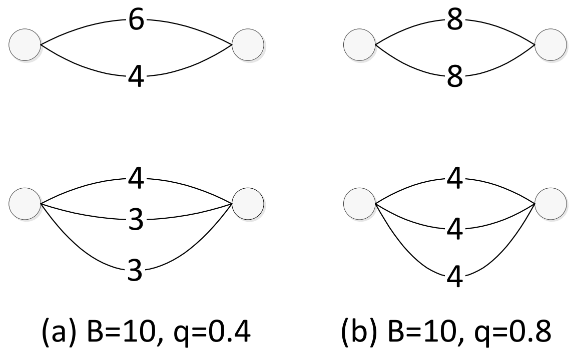


Fig. 1. Example solutions for two demands with the same bandwidth requirement and different protection requirement.

Figure 1 shows example solutions for two demands with the same bandwidth requirement and different protection requirement. Specifically, Fig. 1(a) shows a two-path solution and a three-path solution for a demand with $B = 10$ and $q = 0.4$, and Fig. 1(b) shows a two-path solution and a three-path solution for a demand with $B = 10$ and $q = 0.8$. The number on each path indicates the number of subcarriers allocated on the path. It is easy to verify that the two solutions for each demand satisfy both the bandwidth requirement and the protection requirement of the demand. We note that for the demand with $B = 10$ and $q = 0.4$, the total allocated subcarriers on all the routing paths in a solution is equal to B $(6 + 4 = 10$ in the two-path solution and $4 + 3 + 3 = 10$ in the three-path solution). On the other hand, for the demand with $B = 10$ and $q = 0.8$, the total allocated subcarriers on all the routing paths in a solution is greater than B $(8 + 8 = 16 > 10$ in the two-path solution and $4 + 4 + 4 = 12 > 10$ in the three-path solution). In general, when $q \le 0.5$, the solutions have the property that the total allocated subcarriers on all the routing paths is equal to B; when $q > 0.5$, the solutions have the property that the total allocated subcarriers on all the routing paths is greater than or equal to B. These properties are used in the design of the heuristic algorithm presented in Section IV.

III. ILP Model for the Dynamic SM-RSA Problem

In this section, we present an ILP model for the dynamic SM-RSA problem. The purpose of the ILP model is to compute an SM-RSA solution for a given demand that minimizes the total allocated subcarriers for the demand. For each ordered pair of nodes (u, v) in the network, we precompute a set of candidate link-disjoint paths $\mathbf{P}_{u,v}$ $(|\mathbf{P}_{u,v}| \ge 2)$ from u to v. Here, Bhandari's link-disjoint paths algorithm [20] is used to compute the largest number of link-disjoint paths with the least total cost for a given pair of source and destination nodes.

The ILP model for a request $r = \langle s, d, B, q \rangle$ is given below:

Notations

K: The number of link-disjoint paths in $\mathbf{P}_{s,d}$, $K = |\mathbf{P}_{s,d}|$.

p_k: The kth link-disjoint path in $\mathbf{P}_{s,d}$. $1 \le k \le K$.

L_k: Length of path p_k in hops.
n: The total number of subcarriers on each link.
U_k^w: Boolean parameter that equals 1 if subcarrier w ($1 \le w \le n$) is not available on path p_k (i.e., subcarrier w is not available on at least one link of p_k), and equals 0 if subcarrier w is available on p_k (i.e., subcarrier w is available on every link of p_k).
G: The number of guard subcarriers.

Variables
S_k^w: Boolean variable that equals 1 if path p_k is allocated subcarrier w and 0 otherwise.
X_k: Boolean variable that equals 1 if path p_k is used to accommodate request r and 0 otherwise.

Objective

$$\text{minimize} \sum_{w\in[1,n]} \sum_{k\in[1,K]} S_k^w \cdot L_k,$$

subject to the following constraints:

- **Capacity allocation constraints**

$$\sum_{k\in[1,K]} \sum_{w\in[1,n]} S_k^w \ge B + \sum_{k\in[1,K]} X_k \cdot G, \tag{1}$$

$$\sum_{k\in[1,K],k\ne m} \sum_{w\in[1,n]} S_k^w \ge qB + \left(\sum_{k\in[1,K]} X_k - 1\right) \cdot G \quad \forall\, m \in [1,K]. \tag{2}$$

Equation (1) ensures that the bandwidth requirement of the demand is satisfied. Equation (2) guarantees that the protection requirement of the demand is satisfied. The right-hand side of Eqs. (1) and (2) takes into account G guard subcarriers on each routing path. That is, the subcarriers allocated on each routing path include G guard subcarriers to satisfy the guard subcarrier constraint.

- **Per path guard subcarrier constraint**

$$\sum_{w\in[1,n]} S_k^w > G \cdot X_k \quad \forall\, k. \tag{3}$$

Equation (3) ensures that G guard subcarriers are allocated on every selected routing path.

- **Number of path constraints**

$$\sum_{k\in[1,K]} X_k \le 3, \tag{4}$$

$$\sum_{k\in[1,K]} X_k \ge 2. \tag{5}$$

Equations (4) and (5) limit the number of paths used to be either two or three. We choose to route a demand over two or three paths because the numerical results for the static SM-RSA problem in [19] show that no more than three candidate paths are used in optimal and heuristic solutions. Although using more routing paths results in more backup capacity saving, it is not cost effective to use more than three paths since the overhead of guard subcarriers and the larger number of subcarriers needed due to the use of longer paths generally outweigh the savings in backup capacity [19].

- **Spectrum contiguity constraint**

$$(S_k^w - S_k^{w+1} - 1)(-n) \ge \sum_{w'\in[w+2,n]} S_k^{w'} \quad \forall\, w,k. \tag{6}$$

Equation (6) ensures that contiguous subcarriers are allocated on a path. If path p_k uses subcarrier w and does not use subcarrier $w+1$, then it cannot use any subcarrier with index $w' \in [w+2, n]$.

- **Nonoverlapping spectrum constraints**

$$U_k^w \cdot S_k^w \le 0 \quad \forall\, k,w. \tag{7}$$

Equation (7) ensures that subcarrier w cannot be allocated on path p_k if it is not available on the path.

- **Path selection constraints**

$$\sum_{w\in[1,n]} S_k^w \le X_k \cdot n \quad \forall\, k, \tag{8}$$

$$X_k \le \sum_{w\in[1,n]} S_k^w \quad \forall\, k. \tag{9}$$

Equations (8) and (9) ensure the correctness of the value of X_k. Equation (8) ensures that if one or more subcarriers are allocated on path p_k, then path p_k is marked as used. Equation (9) ensures that if no subcarrier is allocated on path p_k, then path p_k is marked as unused.

IV. Heuristic Algorithm for the Dynamic SM-RSA Problem

In this section, we present a heuristic algorithm for the dynamic SM-RSA problem. For each pair of nodes (u,v) in the network, we precompute a set of candidate link-disjoint paths $\mathbf{P}_{u,v}$ ($|\mathbf{P}_{u,v}| \ge 2$) between u and v using Bhandari's link-disjoint paths algorithm [20]. We also sort the paths in $\mathbf{P}_{u,v}$ in increasing order of hop count. When a request $r = \langle s,d,B,q\rangle$ arrives at the network, the heuristic algorithm selects N ($2 \le N \le 3$) routing paths from $\mathbf{P}_{s,d}$ and allocates an appropriate number of subcarriers on each of the N paths using the available subcarriers in the network. The constraints given in Section II are taken into account when serving a demand.

Algorithm 1 Heuristic Algorithm for Dynamic SM-RSA

```
1: if q ≤ 0.5 then
2:    call Algorithm 2 and return its solution
3: else
4:    call Algorithm 3 and save its solution in S_2path
5:    call Algorithm 4 and save its solution in S_3path
6:    if total allocated subcarriers in S_2path ≤ total allocated
      subcarriers in S_3path then
7:       return S_2path
8:    else
9:       return S_3path
10:   end if
11: end if
```

The pseudo code of the heuristic algorithm is given in **Algorithm 1**. This algorithm computes a dynamic

SM-RSA solution for a given request $r = \langle s, d, B, q \rangle$. It calls other algorithms depending on the value of q. When $q \le 0.5$, it calls **Algorithm 2**. When $q > 0.5$, it calls **Algorithm 3** to get a two-path solution and calls **Algorithm 4** to get a three-path solution. It then compares the two solutions in terms of the total number of subcarriers allocated to r and returns the solution with fewer allocated subcarriers. For all these four algorithms, the input is a request $r = \langle s, d, B, q \rangle$ and the outputs are the routing paths selected for r and the number of subcarriers to be allocated on each of the routing paths. We distinguish between the case $q \le 0.5$ and the case $q > 0.5$ because the total allocated subcarriers on all the routing paths in a solution is always equal to B in the former case but can be greater than B in the latter case, as discussed in Section II.

Algorithm 2 Algorithm for a Request With $q \le 0.5$

1: **for** each path i in $\mathbf{P}_{s,d}$ **do**
2: **if** MCS of path $i > G$ **then**
3: $mcs1 =$ MCS of path i
4: **else**
5: continue to next i
6: **end if**
7: **for** each path $j > i$ in $\mathbf{P}_{s,d}$ **do**
8: **if** MCS of path $j > G$ **then**
9: $mcs2 =$ MCS of path j
10: **else**
11: continue to next j
12: **end if**
13: **if** $mcs1 + mcs2 < qB + 2G$ **then**
14: continue to next j
15: **else**
16: $alloc1 = \min(B - qB + G, mcs1)$
17: $alloc2 = \min(B - alloc1 + 2G, mcs2)$
18: **if** $alloc2 > B - qB + G$ **then**
19: $alloc2 = B - qB + G$
20: **end if**
21: **if** $alloc1 + alloc2 < B + 2G$ **or** $alloc1 < qB + G$ **or** $alloc2 < qB + G$ **then**
22: **for** each path $k > j$ in $\mathbf{P}_{s,d}$ **do**
23: **if** MCS of path $k > G$ **then**
24: $mcs3 =$ MCS MCS of path k
25: **else**
26: continue to next k
27: **end if**
28: $alloc3 = B + 3G - alloc1 - alloc2$
29: **if** $alloc3 \le mcs3$ **then**
30: **return** paths i,j,k and $\lceil alloc1 \rceil$, $\lceil alloc2 \rceil$, $\lceil alloc3 \rceil$
31: **else**
32: continue to next k
33: **end if**
34: **end for**
35: **else**
36: **return** paths i,j and $\lceil alloc1 \rceil$, $\lceil alloc2 \rceil$
37: **end if**
38: **end if**
39: **end for**
40: **end for**

Algorithm 2 computes an SM-RSA solution for $r = \langle s, d, B, q \rangle$ when $q \le 0.5$. The basic idea of **Algorithm 2** is the following. Starting with $i = 1$, it tries to find a two-path solution that includes paths i and j ($j > i$) in $\mathbf{P}_{s,d}$. If such a solution is found, then return it. Otherwise it tries to find a three-path solution that includes paths i, j, k ($k > j > i$) in $\mathbf{P}_{s,d}$. If such a solution is found, then return it. Otherwise increase i by 1 and repeat the above. The algorithm also tries to allocate more subcarriers on shorter paths to reduce the total number of subcarriers allocated to the demand. We now explain the details of the algorithm. In lines 1–14, it tries to find two candidate paths i and j such that each path's maximum contiguous subcarriers (MCS) is more than G to ensure that there are enough subcarriers to satisfy the guard subcarrier requirement. Here the MCS of a path is defined as the maximum number of contiguous subcarriers available on the path. Lines 13 and 14 ensure that the sum of the MCS of path i (i.e., the first path) and path j (i.e., the second path) can satisfy the protection requirement and the guard subcarrier requirement. Then, from line 16 to line 20, it tries to find a two-path solution by allocating subcarriers on the two paths. In line 16, the algorithm tries to allocate $B - qB + G$ subcarriers on the first path. Since $q \le 0.5$ and the first path is shorter than the second path, this will lead to a solution with minimum cost. The allocation on the first path is denoted as $alloc1$. In line 17, the algorithm tries to allocate $B - alloc1 + 2G$ subcarriers on the second path. The allocation on the second path is denoted as $alloc2$. In lines 18–20, $alloc2$ is reduced to $B - qB + G$ if it is greater than $B - qB + G$. We ensure that the number of subcarriers allocated on each path is no more than $B - qB + G$ as the other path must have at least $qB + G$ subcarriers allocated to it. Line 21 checks if $alloc1$ and $alloc2$ violate the bandwidth requirement or the protection requirement. If not, then a two-path solution is returned in line 36 (we return the ceiling of $alloc1$ and $alloc2$ to ensure integer allocations). Otherwise, a third path is needed. To obtain the third path, lines 22–27 find a candidate path k (i.e., the third path) with MCS more than G. Line 28 allocates subcarriers on the third path to satisfy the bandwidth requirement. If the third path has enough free subcarriers to accommodate the allocation, then a three-path solution is returned (lines 29 and 30). Here, we return the ceiling of $alloc1$, $alloc2$, and $alloc3$ to ensure integer allocations. Note that $alloc1$, $alloc2$, and $alloc3$ satisfy the bandwidth requirement B because the calculation of $alloc3$ in line 28 guarantees it. In addition, we know that 1) $alloc1 + alloc2 \ge qB + 2G$ because of the check in line 13, 2) $alloc1 + alloc3 \ge qB + 2G$ because $alloc1 + alloc2 + alloc3 = B + 3G$ (line 28) and $alloc2 \le B - qB + G$ (lines 18–20), and 3) $alloc2 + alloc3 \ge qB + 2G$ because $alloc1 + alloc2 + alloc3 = B + 3G$ (line 28) and $alloc1 \le B - qB + G$ (line 16). Thus, the protection requirement is also satisfied. If the condition in line 29 is not satisfied (i.e., there are not enough free subcarriers to accommodate $alloc3$ on the third path), the algorithm will go back to line 22 to find another candidate path to serve as the third routing path.

Algorithm 3 Algorithm for Computing a Two-Path Solution When $q > 0.5$

for each path i in $\mathbf{P}_{s,d}$ **do**
  if MCS of path $i \geq qB + G$ **then**
    $alloc1 = qB + G$
  else
    continue to next i
  end if
  for each path $j > i$ in $\mathbf{P}_{s,d}$ **do**
    if MCS of path $j \geq qB + G$ **then**
      $alloc2 = qB + G$
      return paths i,j and $\lceil alloc1 \rceil, \lceil alloc2 \rceil$
    else
      continue to next j
    end if
  end for
end for

Algorithm 3 computes a two-path dynamic SM-RSA solution for r when $q > 0.5$. It finds the first two paths in the candidate path set of r such that each of them has at least $qB + G$ contiguous free subcarriers. By allocating $qB + G$ subcarriers on each of the two paths, the algorithm ensures that the bandwidth requirement, the protection requirement, and the guard subcarrier requirement are all satisfied.

Algorithm 4 Algorithm for Computing a Three-Path Solution When $q > 0.5$

1: **for** each path i in $\mathbf{P}_{s,d}$ **do**
2:   **if** MCS of path $i > G$ **then**
3:     $mcs1 =$ MCS of path i
4:   **else**
5:     continue to next i
6:   **end if**
7:   **for** each path $j > i$ in $P_{s,d}$ **do**
8:     **if** MCS of path $j > G$ **then**
9:       $mcs2 =$ MCS of path j
10:     **else**
11:       continue to next j
12:     **end if**
13:     **if** $mcs1 + mcs2 < qB + 2G$ **then**
14:       continue to next j
15:     **else**
16:       **for** each path $k > j$ in $P_{s,d}$ **do**
17:         **if** MCS of path $k > G$ **then**
18:           $mcs3 =$ MCS of path k
19:         **else**
20:           continue to next k
21:         **end if**
22:         **if** $mcs1 + mcs3 < qB + 2G$ **or** $mcs2 + mcs3 < qB + 2G$ **or** $mcs1 + mcs2 + mcs3 < B + 3G$ **then**
23:           continue to next k
24:         **end if**
25:         $alloc1 = \min(qB/2 + G, mcs1)$
26:         $alloc2 = qB + 2G - alloc1$
27:         **if** $alloc2 > mcs2$ **then**
28:           $alloc2 = mcs2$
29:           $alloc1 = alloc1 + (alloc2 - mcs2)$
30:         **end if**
31:         $alloc3 = qB + 2G - \min(alloc1, alloc2)$
32:         **if** $alloc3 > mcs3$ **then**
33:           $alloc3 = mcs3$
34:           **if** $alloc1 + alloc3 < qB + 2G$ **then**
35:             $alloc1 = qB + 2G - alloc3$
36:           **end if**
37:           **if** $alloc2 + alloc3 < qB + 2G$ **then**
38:             $alloc2 = qB + 2G - alloc3$
39:           **end if**
40:         **end if**
41:         **if** $alloc1 + alloc2 + alloc3 < B + 3G$ **then**
42:           $diff = B + 3G - alloc1 - alloc2 - alloc3$
43:           Sequentially increase $alloc1$ up to $mcs1$, $alloc2$ up to $mcs2$, $alloc3$ up to $mcs3$ until total increment is equal to $diff$
44:         **end if**
45:         **return** paths i,j,k and $\lceil alloc1 \rceil$, $\lceil alloc2 \rceil$, $\lceil alloc3 \rceil$
46:       **end for**
47:     **end if**
48:   **end for**
49: **end for**

Algorithm 4 computes a three-path dynamic SM-RSA solution for r when $q > 0.5$. From line 1 to line 24, it tries to find three candidate routing paths i, j, k $(k > j > i)$ for r. In line 13 and line 22, it ensures that the three candidate paths have enough free contiguous subcarriers to satisfy the bandwidth and protection requirements. From line 25 to line 40, the algorithm computes the subcarrier allocation on the three candidate routing paths. First, $alloc1$ is calculated in line 25 to allocate at most $qB/2 + G$ subcarriers on the first path. Then $alloc2$ is calculated in line 26 to allocate $qB + 2G - alloc1$ subcarriers on the second path. This ensures that the allocation on the first two paths satisfies the protection requirement. In line 27, it checks if $alloc2 > mcs2$. If so, then there are not enough free subcarriers on the second path to accommodate $alloc2$. In this case, $alloc2$ is set to $mcs2$ and $alloc1$ is increased by $alloc2 - mcs2$ (lines 28 and 29) to ensure that the first two paths still satisfy the protection requirement. Note that we can safely increase $alloc1$ in line 29 because the check in lines 13 and 14 ensures that $mcs1 + mcs2$ is at least $qB + 2G$. In line 31, $alloc3$ is calculated to be the number of subcarriers required on the third path to satisfy the protection requirement. In line 32, it checks if $alloc3 > mcs3$. If so, then there are not enough free subcarriers on the third path to accommodate $alloc3$. In this case, $alloc3$ is set to $mcs3$ (line 33), and $alloc1$ and $alloc2$ are recalculated (lines 34–39) to ensure that the three candidate paths still satisfy the protection requirement. The new values of $alloc1$ and $alloc2$ might be larger than their old values. However, it is safe to increase $alloc1$ and $alloc2$ because lines 22 and 23 ensure that each of the first two candidate paths has enough free subcarriers to satisfy the protection requirement when $alloc3$ is set to $mcs3$. Finally, the algorithm checks if the bandwidth requirement is satisfied (line 41). If not, then the deficit of $B + 3G - alloc1 - alloc2 - alloc3$ needs to be distributed to the three paths. In line 43, the algorithm sequentially increases $alloc1$, $alloc2$, and $alloc3$ until the total increase is equal to the deficit. We know that the three candidate paths can accommodate the necessary increase in subcarrier allocation because the check in lines 22 and 23 ensures that $mcs1 + mcs2 + mcs3 \geq B + 3G$. In line 45, the algorithm returns the solution that includes the three routing paths for r and the number of subcarriers to be allocated on each routing path.

A. Subcarrier Allocation

When a request r arrives at the network, **Algorithm 1** is called and it returns the routing paths selected for r and the number of subcarriers to be allocated on each of the routing paths. We then follow the best-fit strategy to allocate subcarriers on the routing paths as follows. We call a set of contiguous available subcarriers on a path a *CAS group* and its size is the number of subcarriers in the group. At any point in time, a path can choose subcarriers from 0 or more CAS groups. To allocate m subcarriers on path p, we will find the smallest CAS group on p with size greater than or equal to m and allocate the first m subcarriers in this group to p. For example, suppose a path p has two CAS groups; the first one contains subcarriers 3–6, and the second one contains subcarriers 10–12. If three subcarriers need to be allocated on p, we will allocate subcarriers 10–12. This best-fit strategy reduces spectral fragmentation as larger CAS groups can be kept to serve future demands with larger bandwidth requirement.

V. Numerical Results

In this section, we evaluate the performance of the ILP model and the heuristic algorithm for the dynamic traffic scenario. We also show the results of an SPP algorithm to demonstrate the advantage of MPP over SPP. The SPP algorithm works as follows. For a given demand $r = \langle s, d, B, q \rangle$, we use Bhandari's algorithm to compute a set of link-disjoint candidate paths for r and sort the candidate paths in increasing order of path length in hops. We find the first candidate path that has at least $B + G$ contiguous available subcarriers. This path is chosen as the working path for r with the first $B + G$ contiguous available subcarriers allocated to it. We then remove the working path from the candidate path set and find the first remaining candidate path that has at least $qB + G$ contiguous available subcarriers. This path is chosen as the backup path for r with the first $qB + G$ contiguous available subcarriers allocated to it.

We use a sample USA network topology with 24 nodes and 43 links as shown in Fig. 2. The arrival of traffic follows a Poisson distribution with λ demands per second. The demand holding time is exponentially distributed with a mean of $1/\mu$. The traffic load measured in erlangs is λ/μ. We conduct simulations for different load values. In each simulation, 10,000 randomly generated demands are loaded to the USA network. Each demand has random source and destination nodes. The bandwidth requirement B is chosen from {10, 20, 30, 40}, and the protection

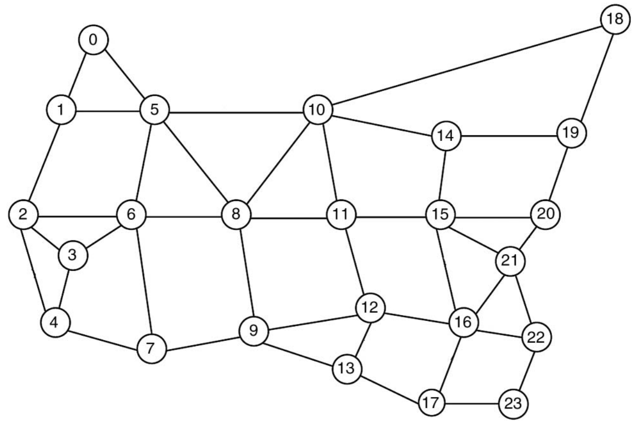


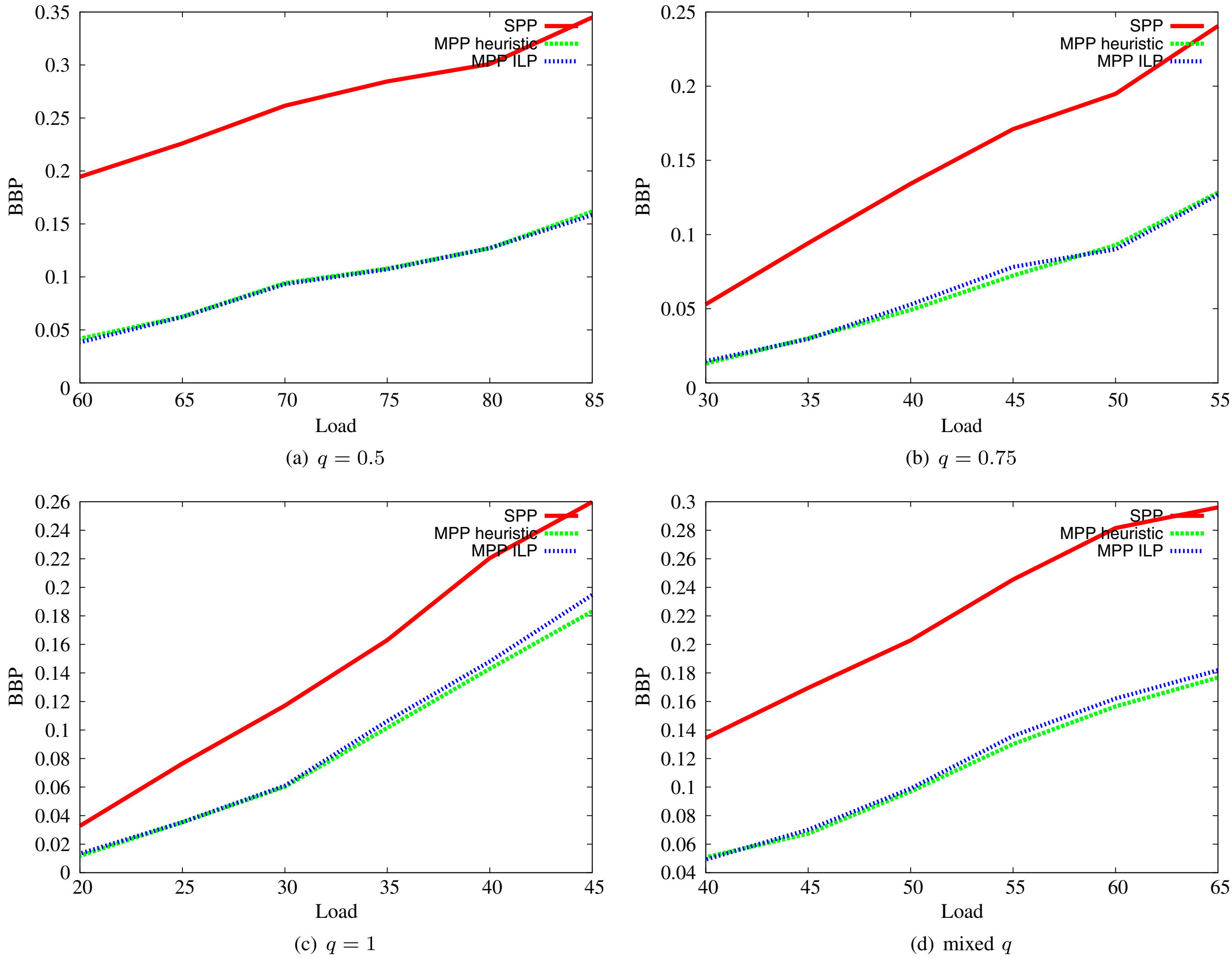
Fig. 2. Sample USA network topology.

requirement q is chosen from {0.5, 0.75, 1}. The number of subcarriers on each link is set to 300. The number of guard subcarriers G is set to 1. We use the metric BBP to evaluate the performance of the different algorithms, where BBP is the ratio of blocked bandwidth to total requested bandwidth.

A. Blocking Performance Comparison Between SPP and MPP

Figure 3 contains four subfigures that show the BBP of SPP, MPP ILP, and MPP heuristic as a function of load for different q values. In Figs. 3(a)–3(c), all demands have a q value of 0.5, 0.75, and 1, respectively. In Fig. 3(d), each demand's q value is randomly chosen from {0.5, 0.75, 1}. In each of the four subfigures, the load values are chosen such that BBP of MPP is within the range 0.01–0.2. Thus, the range of load values is different for each subfigure. For $q = 0.5$, $q = 0.75$, and $q = 1$, the range of load values is 60–85, 30–55, and 20–45, respectively. For mixed q, the load values are in the range 40–65. From Figs. 3(a)–3(c) we can see that the network is able to carry more traffic when the q value decreases. For example, $\text{BBP} = 0.1$ is achieved at load 35 when $q = 1$. The same BBP is achieved at load 50 when $q = 0.75$ and at load 75 when $q = 0.5$.

We see from Fig. 3 that in all the cases SPP's BBP is significantly higher than MPP ILP and MPP heuristic's BBP, and MPP ILP and MPP heuristic have similar BBP. This shows the clear advantage of MPP over SPP. To study the relative performance of SPP and MPP, we compute the ratio of SPP's BBP to MPP heuristic's BBP for different q and load values, and the results are listed in Table I. We see that the ratio is over 2 in most of the cases and can be as high as 4.67. That is, MPP heuristic's BBP is less than half of SPP's BBP in most of the cases. We also observe from Table I that the ratio decreases as the load increases for each q value. This means that the performance advantage of MPP over SPP is bigger when the load is smaller. In practice, the network should operate with low BBP (e.g., less than 5%); this corresponds to the low load values in Fig. 3 where the advantage of MPP over SPP is the greatest.



(a) $q = 0.5$

(b) $q = 0.75$

(c) $q = 1$

(d) mixed q

Fig. 3. BBP of SPP, MPP heuristic, and MPP ILP as a function of load under different q values.

Another interesting finding from Table I is that the performance gap between SPP and MPP gets smaller when q gets larger. Specifically, when $q = 0.5$, the ratio of SPP's BBP to MPP heuristic's BBP is in the range of 2.13–4.67; when $q = 0.75$, the range of the ratio decreases to 1.88–4.06; when $q = 1$, the range of the ratio further decreases to 1.42–2.77. This can be explained as follows. When $q = 0.5$, SPP requires B subcarriers on the working path and $0.5B$ subcarriers on the backup path. If two paths are utilized in MPP, only $0.5B$ subcarriers are needed on each path. So MPP is able to save $0.5B$ subcarriers by using the same number of paths as SPP. On the other hand, when $q = 1$, if two paths are employed in MPP, then each path needs B subcarriers, which is the same as SPP. MPP may utilize more than two paths to improve spectral efficiency. However, when more paths are used, more guard subcarriers are required. Also, longer paths will be used which occupy more subcarriers. These factors cause the performance gap between MPP and SPP to become smaller when q gets larger.

TABLE I
RATIO OF SPP'S BBP TO MPP HEURISTIC'S BBP FOR DIFFERENT q AND LOAD VALUES

q	Load1	Load2	Load3	Load4	Load5	Load6
0.5	4.67	3.62	2.78	2.64	2.37	2.13
0.75	4.06	3.13	2.73	2.36	2.10	1.88
1.0	2.77	2.16	1.95	1.61	1.54	1.42
Mixed	2.64	2.52	2.09	1.89	1.80	1.68

B. Fairness Comparison Between SPP and MPP

It has been shown in [21] that a high degree of unfairness in call blocking may arise in multirate flexible optical networks where high bandwidth demanding services experience much higher call blocking than low bandwidth demanding services. In [21], the authors consider different services sharing a given optical link, and the services do not have a protection requirement. In this section, we evaluate the fairness of SPP and MPP in the USA network for requests with both bandwidth and protection requirements.

Table II shows the drop rate of SPP for $B = 40$ (i.e., high bandwidth requests) and $B = 10$ (i.e., low bandwidth

TABLE II
DROP RATE OF SPP AND MPP HEURISTIC FOR $B = 40$ AND $B = 10$

q	Load	SPP40	MPP40	SPP10	MPP10
0.5	85	0.54	0.26	0.02	0.02
0.5	60	0.34	0.067	0.0028	0.0024
0.75	55	0.38	0.20	0.011	0.012
0.75	30	0.099	0.021	0.0012	0.0008
1	45	0.43	0.28	0.010	0.022
1	20	0.063	0.021	0	0
Mixed	65	0.46	0.27	0.019	0.018
Mixed	40	0.23	0.082	0.004	0.002

requests), and the drop rate of MPP heuristic for $B = 40$ and $B = 10$. For each q value, the drop rates for the lowest simulated load and the highest simulated load are listed in the table. We see from Table II that for a given q value and a given load, SPP's drop rate for $B = 40$ is much higher than that for $B = 10$. Similarly, MPP heuristic's drop rate for $B = 40$ is much higher than that for $B = 10$. This means that both SPP and MPP give a significant advantage to low bandwidth requests. We also observe from Table II that the drop rate of MPP heuristic is much lower than the drop rate of SPP for $B = 40$. On the other hand, the drop rate of MPP heuristic and the drop rate of SPP are similar for $B = 10$. This means that MPP is relatively fairer than SPP as it can accommodate much more large bandwidth requests than SPP while accommodating about the same amount of low bandwidth requests as SPP.

Table III shows SPP's ratio of drop rate for $B = 40$ to drop rate for $B = 10$ (column heading SPP40/SPP10) and MPP heuristic's ratio of drop rate for $B = 40$ to drop rate for $B = 10$ (column heading MPP40/MPP10). As in Table II, the ratios for the lowest simulated load and the highest simulated load are listed for each q value in Table III. When $q = 1$ and load $= 20$, SPP40/SPP10 and MPP40/MPP10 values are N/A because the drop rate for SPP10 and MPP10 is 0. We see from Table III that both SPP and MPP have high ratios: for SPP the ratio is between 23.88 and 120.66, and for MPP the ratio is between 12.79 and 40.70. This means that both SPP and MPP favor low bandwidth requests, i.e., low bandwidth requests have much lower drop rate than high bandwidth requests. If we look at MPP and SPP's ratios in the same row (i.e., their ratios for a given q value and a given load), we see that SPP's ratio is always higher than MPP's ratio. This means that SPP

TABLE III
SPP AND MPP HEURISTIC'S RATIO OF DROP RATE FOR $B = 40$ TO DROP RATE FOR $B = 10$

q	Load	SPP40/SPP10	MPP40/MPP10
0.5	85	34.77	13.22
0.5	60	120.66	28.19
0.75	55	35.20	15.86
0.75	30	81.94	26.37
1	45	42.60	12.79
1	20	N/A	N/A
Mixed	65	23.88	15.05
Mixed	40	52.38	40.71

results in more dramatic difference in the drop rate between low bandwidth requests and high bandwidth requests. Thus, MPP is relatively fairer than SPP.

C. Comparison of MPP ILP and MPP Heuristic

We see from Fig. 3 that MPP heuristic and MPP ILP have similar BBP performance in all the cases. For $q = 0.5$, ILP performs slightly better than the heuristic. For $q = 0.75$, neither of the two algorithms is consistently better than the other. For $q = 1$ and mixed q, the heuristic performs better than the ILP. Note that the ILP's objective is to minimize the total allocated subcarriers for a given demand. This objective does not lead to minimum BBP for dynamic demands. The ILP will accept a demand whenever there is enough spectrum resource to accommodate the demand. On the other hand, the heuristic may reject a demand even though there is enough spectrum resource to accommodate it. This may cause more future demands to be accepted. This explains why the heuristic performs better than the ILP in some cases.

In terms of the running time, the heuristic is much faster than the ILP. The ILP takes up to 1.2 s to compute a solution for each request, while the heuristic takes about 4.5 ms to obtain a solution. Since the heuristic is significantly faster than the ILP while having similar blocking performance to the ILP, MPP heuristic is the algorithm of choice for practical networks.

VI. CONCLUSION

OFDM-based optical networks can efficiently accommodate variable bitrate traffic due to its fine granularity and flexible bandwidth allocation capability. In this paper, we study the dynamic SM-RSA problem. Given a demand with bandwidth and protection requirements, the problem is to find two or more routing paths for the demand and allocate subcarriers on the routing paths such that the bandwidth and protection requirements are satisfied. We develop an ILP model as well as a heuristic algorithm for the problem. Our simulation results demonstrate that (1) our MPP scheme achieves significantly lower BBP than the conventional SPP scheme, (2) the MPP heuristic algorithm achieves similar blocking performance to the MPP ILP while being significantly faster, and (3) both SPP and MPP are unfair to large bandwidth requests, but MPP is relatively fairer than SPP. The MPP algorithms presented in this paper did not address the differential delay between multiple routing paths, and this may cause the reordering problem at the end nodes [14,15]. In our future work we will improve our algorithms with the consideration of differential delay. We will also investigate techniques to improve the fairness of the MPP scheme.

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