Survivable Multipath Provisioning in OFDM-Based Flexible Optical Networks

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Abstract—OFDM-based flexible optical networks provide better spectral efficiency than conventional WDM optical networks as connections can be allocated requested capacity instead of full wavelength capacity. Survivability is an important issue in OFDM-based flexible optical networks. However, little work has been done in this area. In this study, we propose a survivable multipath provisioning scheme that provides flexible protection levels to individual connections in OFDM-based flexible optical networks. We define the static Survivable Multipath Routing and Spectrum Allocation (SM-RSA) problem which seeks to accommodate a given set of demands using multipath provisioning such that the utilized spectrum is minimized. We show that the static SM-RSA problem is NP-hard and present an efficient heuristic algorithm to solve the problem. Our simulation results show that the proposed multipath provisioning scheme achieves better spectral efficiency than the conventional single-path provisioning scheme.

I. INTRODUCTION

In conventional WDM optical networks, a connection is supported by a lightpath with full wavelength capacity. This rigid and coarse granularity leads to waste of capacity when the traffic between the end nodes is less than the capacity of a wavelength. To address this issue, flexible optical networks with fine granularity are needed for better spectral efficiency. Orthogonal frequency division multiplexing (OFDM), a modulation technique used extensively in broadband wired and wireless communication systems, is also a promising 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 provide fine granularity capacity, as opposed to wavelength capacity, to connections. A novel OFDM-based optical transport network architecture called spectrum-sliced elastic optical path network (SLICE) is proposed in [3]. In SLICE networks, just enough spectral resource is allocated to an end-to-end optical path according to the user demand, leading to efficient accommodation of sub-wavelength and super-wavelength traffic. The performance superiority of OFDM-based flexible optical networks over conventional WDM optical networks has been demonstrated in [4], [5], [6], [7].

Survivability is a crucial requirement in optical transport networks as network failures such as fiber cuts can cause tremendous loss of data and revenue. Survivability in OFDM-based flexible optical networks is a relatively new topic that has not received much study. The authors in [8] propose a heuristic algorithm for survivable flexible WDM network design. In [9], two backup sharing policies for OFDM-based optical networks are proposed and evaluated. Both [8] and [9] consider single path provisioning with full protection. That is, a demand is provisioned on a single working path and a link-disjoint backup path is used to provide full protection against any single link failure.

In this paper, we propose a new survivable MultiPath Provisioning (MPP) scheme for OFDM-based flexible optical networks that supports flexible protection levels (i.e., full protection as well as partial protection) and provides higher spectral efficiency than Single-Path Provisioning (SPP). In multipath provisioning, a data stream is split into multiple lower-rate streams each of which is routed on a separate path. Multipath provisioning naturally provides partial protection because when a failure occurs on one of the connection’s paths, traffic carried on the other paths is not affected. Multipath provisioning schemes providing full protection and partial protection in next-generation SONET/SDH networks with virtual concatenation are presented in [10] and [11] respectively. Partial protection using multipath provisioning in general mesh networks is studied in [12], [13], [14]. In [12], the authors present an online multipath provisioning algorithm that guarantees the maximum partial-protection possible. In [13], a linear program is developed to find a minimum cost multipath routing and capacity allocation strategy to meet the bandwidth requirement and partial protection requirement of a demand. The work in [14] studies the survivable multipath provisioning problem with differential delay constraint. To the best of our knowledge, there is no prior work on survivable multipath provisioning in OFDM-based flexible optical networks.

A key problem in the design and operation of OFDM-based flexible optical networks is the routing and spectrum allocation (RSA) problem which is to select a path and allocate a set of contiguous subcarriers for a demand. The static RSA problem aiming to find the optimal RSA for a given set of demands has been studied in [15], [16]. Optimal ILP formulations as well as heuristic algorithms are presented in these works. In this paper, we define and study the static Survivable Multipath Routing and Spectrum Allocation (SM-RSA) problem in OFDM-based flexible optical networks. In this problem, a set of demands, each having a bandwidth requirement and a protection level requirement, is given. The
objective is to accommodate all the demands using multipath provisioning such that the utilized spectrum is minimized. We propose an efficient heuristic algorithm for the static SM-RSA problem. Numerical results show that the proposed multipath provisioning scheme achieves significant spectrum saving over the single-path provisioning scheme.

The rest of the paper is organized as follows. In Section II, we introduce the survivable multipath provisioning scheme and discuss its advantage over single-path provisioning. In Section III, we define the static SM-RSA problem and show the problem is NP-hard. We propose a heuristic algorithm for the static SM-RSA problem in Section IV and present numerical results in Section V. Finally, we conclude the study in Section VI.

II. THE SURVIVABLE MULTIPATH PROVISIONING SCHEME

The flexible bandwidth allocation capability of OFDM-based optical networks enables the support of flexible protection levels. In this study, we assume a connection request has a bandwidth requirement and a protection level requirement. Specifically, a connection request is represented by \( r = (s, d, B, q) \), where \( s \) and \( d \) are the source and destination nodes, \( B \) is the bandwidth requirement, and \( q \) (0 \( \leq \) \( q \) \( \leq \) 1) is the protection level 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.

To accommodate a connection request \( r = (s, d, B, q) \) using multipath provisioning, we select \( N \geq 2 \) link-disjoint paths between \( s \) and \( d \), and allocate working and backup capacity on each of these paths such that the total working capacity on the \( N \) paths is \( B \) and the total working and backup capacity on any group of \( N - 1 \) paths is \( qB \). Specifically, we allocate \( \frac{B}{N-1} \) working capacity on each path. If \( N \geq \frac{1}{1-q} \), no backup capacity needs to be allocated because each path carries no more than \( (1-q)B \) working capacity. If \( N < \frac{1}{1-q} \), we allocate \( \frac{qB}{N-1} - \frac{B}{N} \) backup capacity on each path. This ensures that any group of \( N-1 \) paths has total capacity \( qB \) so that the protection level requirement is satisfied. The total working and backup capacity allocated on \( N \) paths is \( B \) when \( N \geq \frac{1}{1-q} \) and is \( \frac{qB}{N-1} \) when \( N < \frac{1}{1-q} \).

Table I shows the capacity requirement of multipath provisioning (MPP) for request \( r = (s, d, B, q) \) (bandwidth requirement is 1 and protection level requirement is 0.8) when different number of link-disjoint paths are used. It can be seen that the total capacity allocation decreases as \( N \) increases. When \( N = 5 \), no backup capacity allocation is needed.

In single-path provisioning (SPP), \( r = (s, d, B, q) \) can be accommodated by allocating a working path with capacity \( B \) and a backup path with capacity \( qB \). So the total capacity required is \((1 + q)B \). On the other hand, MPP with \( N = 2 \) requires \( 2qB \) total capacity \((qB \) on each path\). Since \( 1 + q \geq 2q \), MPP with \( N = 2 \) is more efficient than SPP even though both approaches use two link-disjoint paths. For the example request \( r = (s, d, 1, 0.8) \), SPP requires 1 unit capacity on the working path and 0.8 unit capacity on the backup path, giving a total capacity of 1.8 units. This is more than the 1.6 units required in the case of MPP with \( N = 2 \). It can be seen from the above analysis that MPP is more efficient than SPP and the efficiency gap between the two schemes becomes bigger as the number of link-disjoint paths used in MPP increases.

III. THE STATIC SURVIVABLE MULTIPATH ROUTING AND SPECTRUM ALLOCATION PROBLEM

In OFDM-based flexible optical networks, the frequency spectrum is divided into a number of subcarriers or slots with equal frequency. Accommodating a demand using SPP requires selecting a route and allocating contiguous subcarriers on each link on the route. This is called the routing and spectrum allocation (RSA) problem. Accommodating a given set of demands while minimizing the utilized spectrum is called the static RSA problem, which is proved to be NP-hard in [16]. Since demands can be accommodated more efficiently using MPP, we define a new problem, the static Survivable Multipath RSA (SM-RSA) problem, as follows: Given a set of traffic demands, each represented by \( r = (s, d, B, q) \), accommodate all the demands using multipath provisioning such that the maximum occupied subcarrier index is minimized. In this problem, we need to determine two or more link-disjoint paths for each demand and allocate spectrum on each path so that the bandwidth and protection requirements of each demand is satisfied and the utilized spectrum is minimized.

The static SM-RSA problem requires the following constraints to be satisfied.

- Working and backup capacity constraint: For each request \( r = (s, d, B, q) \), the total working capacity allocated to all its paths is \( B \) and the total working and backup capacity remaining after any single link failure is at least \( qB \).
- Spectrum contiguity constraint: A set of contiguous subcarriers must be allocated to a spectrum path.
- Non-overlapping spectrum constraint: A subcarrier on a link can only 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.

The static SM-RSA problem is significantly more complicated than the static RSA problem. In fact, the NP-hard static RSA problem is a special case of the static SM-RSA problem.

<table>
<thead>
<tr>
<th>( N )</th>
<th>Working Capacity Per Path</th>
<th>Backup Capacity Per Path</th>
<th>Total Capacity on ( N ) Paths</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.3</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>0.333</td>
<td>0.067</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>0.0167</td>
<td>1.067</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table I
where each demand is provisioned on a single path and no protection is required. Thus, the static SM-RSA problem is also NP-hard and it is impossible to efficiently solve the static SM-RSA problem for large networks. In the next section, we present an efficient heuristic algorithm to solve the static SM-RSA problem.

IV. A HEURISTIC ALGORITHM FOR THE STATIC SM-RSA PROBLEM

Our heuristic algorithm consists of three steps. In the first step, for each request \( r = \langle s, d, B, q \rangle \), a set of candidate link-disjoint paths \( P_{s,d} \) (\( |P_{s,d}| \geq 2 \)) is computed between \( s \) and \( d \). Here Bhandari’s link-disjoint paths algorithm [17] is used to compute the largest number of link-disjoint paths with the least total cost for each request. In the second step, we sort the demands in some order and then serve them one-by-one. For each demand, we select a number of routing paths from its candidate path set and allocate an appropriate number of subcarriers on these paths. The constraints given in Section III are taken into account when serving each demand. In the third step, we reconfigure some paths of some demands to reduce the maximum occupied subcarrier index. We assume unlimited link capacity, i.e., the number of subcarriers in each link is unbounded. The details of the algorithm are given in the following sections.

A. Single Path Allocation

We associate each link \( e \) in the network with a boolean array \( \sigma_e = (o_{e1}, o_{e2}, ..., o_{ed}) \) to represent the availability of each subcarrier in \( e \). Here, \( d \) represents the maximum subcarrier index in the link. \( o_{ei} \) equals 1 if the \( ith \) subcarrier is available in link \( e \). Suppose \( n \) subcarriers need to be allocated for path \( p \). First, the availability array of path \( p \) is calculated based on the following equation: \( \sigma_p = \&_{e \in P} \sigma_e \). In this equation, \( \& \) donates boolean AND operation. Then, vector \( \sigma_p \) is checked from low index to high index, the first \( n \) contiguous available subcarriers are allocated to path \( p \). Finally, for each link \( e \) in path \( p \), the allocated subcarriers are marked as unavailable in \( \sigma_e \).

B. Single Request Allocation

To accommodate request \( r = \langle s, d, B, q \rangle \), we first select \( N \) paths from \( P_{s,d} \) (\( 2 \leq N \leq |P_{s,d}| \)), and then calculate the working and backup capacity to be allocated on each path using the method given in Section II. The total number of subcarriers required on each path, denoted by \( n \), can be calculated by \( n = \lfloor \frac{B}{q} \rfloor + G \). Here \( A \) is the total working and backup capacity to be allocated on each path, \( C \) is the capacity of a subcarrier, and \( G \) is the number of guard subcarriers.

To determine the value of \( N \), we note that \( N = \lfloor |P_{s,d}| \rfloor \) may not be the best choice although Table I shows that the total path capacity decreases with increasing number of paths. This is because the guard subcarrier overhead increases if more paths are used. Also, a path with more links will occupy more subcarriers than a path with fewer links, so shorter paths are preferable. To determine the number of paths for request \( r \), we order the paths in \( P_{s,d} \) in increasing order of path length (i.e., number of links in the path). Our goal is to satisfy \( r \) with minimum number of occupied subcarriers. Thus, we calculate the total number of subcarriers required when using the first two, first three, ..., first \( |P_{s,d}| - 1 \), and all candidate paths in \( P_{s,d} \). Out of these \( |P_{s,d}| - 1 \) path set choices, the path set that occupies the least subcarriers is selected. Once the path set is determined, we use the method described in Section IV-A to allocate \( n \) contiguous subcarriers for each path.

C. Ordering of Requests

To satisfy a given set of requests, our algorithm sorts these requests and serves each request one-by-one by using the method in section IV-B. We propose two ordering strategies as follows:

- **Largest Demand First (LDF):** We order the requests in decreasing order of bandwidth requirement and serve the request with the largest demand first. If two or more requests have the same demand, we compare their shortest paths in their candidate path sets. The request with the longest shortest path is served first.

- **Longest Path First (LPF):** We order the requests in decreasing order of the shortest path length in the candidate path set of each request. The request with the longest shortest path is served first. If two or more requests have the same shortest path length, we compare their requested bandwidth and serve the request with the largest demand first.

D. Path Reconfiguration

After serving all requests in LDF or LPF order, we employ a path reconfiguration step to reduce the maximum occupied subcarrier index. The idea is to iteratively reroute the path that currently occupies the largest subcarrier index so that it can be allocated the lowest available subcarriers. This idea is similar to the defragmentation technique proposed in [18], which applies to dynamic traffic scenario where the connection setup and teardown processes lead to fragmentation of spectral resources. The defragmentation algorithms in [18] can be applied periodically to consolidate the available network resources, bringing the network to its optimal state. Our path reconfiguration procedure is different from the defragmentation algorithms in that it applies to static traffic to reduce the utilized spectrum. Also, we consider multipath provisioning instead of single-path provisioning as in [18].

The path reconfiguration procedure works as follows. First, we sort allocated spectrum paths in decreasing order of their largest occupied subcarrier index. Then the first spectrum path from the ordered list, denoted by \( p \), is selected. Suppose \( p \) is allocated \( n \) subcarriers. Set \( i \) to the lowest subcarrier index and construct an auxiliary graph \( G \) in which an edge between a pair of nodes exists if starting from subcarrier \( i \), \( n \) contiguous subcarriers are available on the link connecting the two nodes. Let \( S_p \) be the set of all other link-disjoint paths that belong to the same request’s path set as \( p \). Delete all edges used by the the paths in \( S_p \) from \( G \) and then find the shortest path between
the source and destination of the request. If a path exists, then reconfigure \( p \) using the found path and allocate \( n \) contiguous subcarriers starting from subcarrier \( i \). If a path does not exist, we increment \( i \) and construct a new auxiliary graph until a new path for \( p \) is found or \( i \) equals the current start subcarrier index of \( p \). We keep reconfiguring paths from the ordered list until we reach a path that cannot be reconfigured. That means the maximum occupied subcarrier index of the network cannot be further reduced.

V. NUMERICAL RESULTS

![Fig. 1. A sample US network topology.](image)

In this section, we present the simulation results to demonstrate the performance of our heuristic algorithm. We used a sample US network topology with 24 nodes and 43 links as shown in Fig. 1. We considered two demand sets representing low load and high load cases. In both cases, there is one demand for each ordered pair of nodes in the network, leading to a total of \( 24 \times 23 = 552 \) demands. In the low load demand set, the bandwidth requirement of a demand is a random number between 1 and 10 representing the number of subcarriers required. In the high load demand set, the bandwidth requirement of a demand is a random number between 1 and 40. For both demand sets, we tested three protection levels: 0.5, 0.75 and 1. Note that multipath provisioning offers at least 0.5 protection level due to the use of at least two paths.

A. Comparison between SPP and MPP

First, we compare the spectrum requirement of SPP and MPP schemes. For a request \( r = < s, d, B, q > \), SPP allocates a working path with capacity \( B \) and a backup path with capacity \( qB \) while MPP employs two or more paths and allocates working and backup capacity on each path. Fig. 2 shows the maximum occupied subcarrier index of SPP schemes and MPP schemes under different protection levels for low load case and high load case with \( G = 2 \) (i.e., 2 guard subcarriers). The no protection case is also shown for reference. In the no protection case, each demand is provisioned on a single working path with required capacity. The figure shows that MPP requires less spectrum than SPP in all cases. Also, the performance gap between SPP and MPP is bigger when the protection level is lower. When \( q = 0.5 \), MPP without path reconfiguration achieves a spectrum saving of about 20% and 28% over SPP in the low load case and high load case respectively. For the high load case with \( q = 0.5 \), MPP without path reconfiguration only requires about 12% more spectrum than the no protection case. Note that when \( q = 0.5 \) MPP requires no backup capacity due to the splitting of traffic over two paths. However, MPP still requires more spectrum than the no protection case for two reasons. First, only one path is allocated for a demand in the no protection case while two paths are allocated to a demand in MPP. As a result, MPP has higher overhead of guard subcarriers than the no protection case. Second, in MPP the second path used by a demand is generally longer than the shortest path. This means that MPP requires more subcarriers to satisfy a demand than the no protection case. When \( q \) increases, MPP tends to use more paths for a demand, so the guard subcarrier overhead and the total occupied subcarriers both increase. This explains why the performance gap between SPP and MPP becomes smaller when \( q \) becomes bigger.

B. Effectiveness of Path Reconfiguration

Our heuristic algorithm employs a path reconfiguration procedure after serving all demands one-by-one to reduce the utilized spectrum. Fig. 2 shows the maximum occupied subcarrier index with and without path reconfiguration under different protection levels. It can be seen that path reconfiguration is effective in reducing the utilized spectrum in all cases. Interestingly, in the high load case \( q = 0.5 \), LDF MPP with path configuration even requires less spectrum than the no protection case.

A side effect of path reconfiguration is that it increases the total number of occupied subcarriers. This can be explained as follows. The candidate paths for a given demand are computed using Bhandari’s algorithm, which finds the maximum number of link-disjoint paths with the least total cost. The new path computed in the reconfiguration step for a given path is based on the availability of contiguous subcarriers in the network links, so the new path contains more links than the old one and occupies more subcarriers. In Table. II, we show the percentage decrease of maximum occupied subcarrier index and percentage increase of total occupied subcarriers after path reconfiguration. We see from the table that under all cases the percentage decrease of utilized spectrum is larger than the percentage increase of total occupied subcarriers. That is, the reduction in utilized spectrum is achieved with relatively small increase in total occupied subcarriers.

C. Comparison between LPF and LDF

We consider two ordering strategies in our heuristic algorithm: longest path first (LPF) and largest demand first (LDF). From Fig. 2, we can see that LDF MPP always performs better than LPF MPP with or without path reconfiguration, except in the case of high load and \( q = 0.75 \). Furthermore, path reconfiguration is more effective when LDF is used. This is supported by the data in Table. II, which shows that in all cases LDF achieves higher percentage decrease of maximum
occupied subcarrier index than LPF. This can be explained as follows. In the path reconfiguration procedure, we reconfigure paths in decreasing order of largest occupied subcarrier index. If we encounter a path that cannot be reconfigured, the maximum occupied subcarrier index cannot be reduced anymore. In LDF, the requests with smaller demands are allocated later than the requests with higher demands in the sequential allocation phase. So in the path reconfiguration phase, the paths with fewer allocated subcarriers are at the beginning of the list. Since paths that require fewer subcarriers are easier to be reconfigured, LDF is able to reconfigure more paths than LPF.

**D. Number of Paths used in MPP**

In our MPP scheme, we select a number of paths from the candidate path set by minimizing the total number of required subcarriers for a given demand. The top two rows of Table III show the number of demands with different candidate path set sizes. For example, there are 132 demands with 2 candidate paths and 12 demands with 5 candidate paths. The lower part of Table III shows the number of candidate paths used by demands in MPP under different loads and protection levels. We see from the table that all demands use only two paths when \( q = 0.5 \). Note that when \( q = 0.5 \), using two or more paths requires no backup capacity. Our scheme uses only two paths because more paths lead to more guard subcarrier overhead and more occupied subcarriers. When \( q > 0.5 \), for some requests, employing more than two paths results in more backup capacity saving than the negative effects of more guard subcarriers and more occupied subcarriers. That is why some requests use three paths when \( q = 0.75 \) and \( q = 1 \). No demands use more than three paths because the negative effects outweigh the saving in backup capacity. Also, we observe that for the same protection level, more demands use 3 paths in the high load case than in the low load case. This is because for the high load case, the overhead of 2 guard subcarriers is relatively small compared to the requested bandwidth of demands.

**E. Effect of Number of Guard Subcarriers**

Fig. 3 shows the maximum occupied subcarrier index of SPP schemes and our heuristics when \( G \) equals 1 and 2 for different protection levels. (Path reconfiguration is used in the heuristics.) We see that our heuristic outperforms the SPP scheme in all cases and using 2 guard subcarriers leads to more utilized spectrum than using 1 guard subcarrier for any fixed scheme. Also, the difference in utilized spectrum between using one and two guard subcarriers is larger in the low load case than in the high load case. For example, in the low load \( q = 0.5 \) case, the LDF heuristic requires 29.93%
more spectrum when the number of guard subcarriers increases from 1 to 2; on the other hand, the increase is only 7.83% in the high load $q = 0.5$ case for the LDF heuristic. The low load case is more sensitive to the increase in the number of guard subcarriers because the overhead of guard subcarriers is relatively high compared to the requested bandwidth of demands.

VI. CONCLUSION

In this work, we propose a survivable multipath provisioning scheme for OFDM-based flexible optical networks that efficiently supports connections with bandwidth and protection requirements. We introduce the static Survivable Multipath Routing and Spectrum Allocation (SM-RSA) problem, show the problem is NP-hard, and present a heuristic algorithm to obtain sub-optimal solutions. The heuristic algorithm sorts the demands in specific order and serves them one-by-one. Then a path reconfiguration procedure is applied to reduce the utilized spectrum. Our simulation results demonstrate the higher spectral efficiency of the multipath provisioning scheme over the single-path provisioning scheme as well as the effectiveness of the path reconfiguration procedure.

REFERENCES