Multipath Routing in Elastic Optical Networks with Distance-adaptive Modulation Formats

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***Abstract*—Elastic optical path networks have been proposed as a promising approach to flexibly use the optical spectrum (hence the name *flexi-grid*) thus overcoming the rigidness of traditional WDM networks where optical channel spacing is equidistant irrespectively of the type of signal transmitted. Past research effort in spectrum allocation focused on single transmission paths with a uniform modulation format in the network. However, by using optical OFDM technologies, the flexi-grid networks can benefit from multipath routing with parallel transmission that uses flexible modulation format assignment. In this paper, we propose novel multipath routing and spectrum assignment (RSA) algorithms with distance-adaptive modulation format assignment and analyze the effectiveness in dynamic traffic scenarios. We show that a combined usage of multipath routing and flexible distance-adaptive modulation format assignment can reduce blocking ratio while consuming portions of spectrum comparable to single path routing. Our results also show that a careful dimensioning of guard-band size is a critical factor, and that the full benefits of parallel transmission can be better achieved in networks requiring a small guard-band size.**

I. Introduction

The ever growing need for bandwidth is driving the optical spectrum to the limit, and various technologies for flexible spectrum usage have been proposed. Of note is the spectrum-sliced elastic optical network (SLICE), where spectrum resource is sliced into frequency slots in forms of sub-carriers with Orthogonal Frequency Division Multiplexing (OFDM) techniques [1], often referred to as *optical OFDM networks*. The parallel nature of OFDM technologies brings high spectrum efficiency as compared to the traditional WDM systems with equidistant spectrum allocation. Consider a client connection in a 100Gbps Ethernet (100GE) network requesting a 40Gbps per wavelength, in WDM networks this would require three wavelengths, resulting in 16.67% of unused bandwidth. Assume ITU-T 50GHz grids are used, the connection would allocate 150GHz spectrum with only 80% spectrum utilization. In contrast, the same connection can be provisioned in an optical OFDM system with 12.5GHz per frequency slot which would allocate the exact bandwidth with only 50GHz spectrum using QPSK as the modulation format.

Up to now, spectrum allocation in optical OFDM networks has used single path routing with a uniform modulation format in the entire network. However, it has been shown that the spectrum continuity and consecutive constraints imposed by the elastic optical network architectures can lead to the so-called *spectrum fragmentation* issue where dynamic connection setup may partition the available spectrum into small noncontiguous spectral strips, decreasing the probability of finding sufficient consecutive spectrum for a new connection request [2]. In addition, the uniform modulation assignment cannot fully utilize the available spectrum, due to the fact that optical transmission systems are commonly designed with consideration of the worst case scenario in terms of transmission performance [3]. A typical design parameter is optical signal-to-noise (OSNR). To ensure that optical signals can be correctly received, the OSNR requirement of the longest path is considered for the whole network. As a result, an OSNR margin exists in shorter paths, which can be utilized to improve the spectrum efficiency by adaptively assigning modulation format based on the channel condition. When only transmission loss is considered, the relation between distance and transmission rate can be given as:

$$C_l = C_0/2 \cdot (1 + log_2(2L/L_1)) \tag{1}$$

where C_0 and L is the capacity and distance of the reference path [4]. Hence, if a frequency slot of 12.5GHz, for instance, can be used to transmit data rate of 40Gbps for a path length of 500km, the same frequency slot can be used to transfer traffic at date rate of 80Gbps within the same OSNR margin when the path length is 250km. Prior work in [3] has in fact shown the validity of distance adaptive spectrum assignment.

In this paper, we analyze the effectiveness of multipath routing and spectrum assignment in optical OFDM networks with distance-adaptive modulation assignment. By using multipath routing, we address the spectrum fragmentation issue, while making full use of OSNR margin on each spectrum path by adaptively assigning modulation format based on the path length. We propose two novel scenarios to study the effectiveness of multipath routing with distance-adaptive modulation format assignment. In the first scenario, multiple paths are computed sequentially. Upon finding a path, a modulation format is assigned and spectrum is allocated for as many paths as need to fulfill the bandwidth requirement. In the second scenario, the goal is to allocate spectrum with a set of pre-computed paths with consideration of the differential delay constraint, which as suggested in ITU-T G.709 [5] cannot be larger than $\pm 125us$ due to the realignment process. The performance observed in the numerical results, in terms of connection blocking ratio and spectrum utilization, shows that the proposed multipath routing and spectrum assignment with distance adaptive modulation format assignment can greatly improve the spectrum efficiency of optical OFDM networks.

Our results also show that a careful dimensioning of the guard-band is a critical factor, and that benefits of parallel transmission can be better achieved in networks with smaller guard-bands.

The rest of the paper is organized as follows. Section II provides a brief literature review. In Section III-B, we provide a background overview and present the proposed scenarios and the corresponding heuristic algorithms. Finally, Section IV discusses the results and Section V concludes the paper.

II. Related Work

Enabling technologies for elastic optical networks have recently gained significant attention in the research and standardization communities. In [1], authors proposed a spectrum sliced elastic optical path network architecture (SLICE) that can effectively utilize the spectrum. The paper also presented the key technologies of elastic networks, such as bandwidth variable transponders, bandwidth variable WXCs and tunable OFDM modulators. Akin to the Routing and Wavelength Assignment (RWA) algorithms in WDM networks, a spectrum path in elastic optical networks is determined by the so-called Routing and Spectrum Assignment (RSA) algorithms, which determine the path from source and destination along with its allocated spectrum. All current RSA algorithm consider single path routing, where a unified modulation format is assumed in the entire network, and multipath routing in elastic networks as in our paper has not been studied to date.

The effects of path length, channel condition and modulation formats have not gained much attention yet. In [6], the authors propose an Integer Linear Programming (ILP) model to minimize the assigned spectrum with a static traffic matrix. In [7], the authors presented a comprehensive study on RSA problem in SLICE networks and proved its NP-hardness. The paper also proposed an ILP model and two heuristics to find spectrum paths using minimal number of sub-carriers. The concept of distance adaptive spectrum resource allocation in elastic optical path networks was first proposed in [3]. The authors studied the spectrum resource allocation considering OSNR degradation and filter narrowing effects in the paths of various lengths. [3] shows that distance adaptive spectrum allocation is a promising approach in elastic optical networks, especially when the channel conditions are known or easy to estimate. In this paper, we show that multipath routing combining with distance adaptive modulation format assignment can further improve not only the spectrum efficiency, but also alleviate the spectrum fragmentation issue and significantly improve connection blocking probability.

III. Multipath Routing and Distance Adaptive Modulation Assignment Algorithms

A. Background

1) Frequency Slot Approach in Elastic Optical Networks: In elastic optical networks, the spectrum is sliced into slots with granularity finer than that is currently used in WDM networks, i.e., 50GHz or 100GHz. While spectrum slices in elastic optical path networks have not been standardized yet,

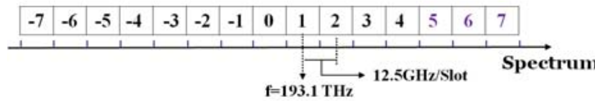


Fig. 1: The Frequency Slot Approach to Slice Spectrum in Elastic Optical Networks [3]

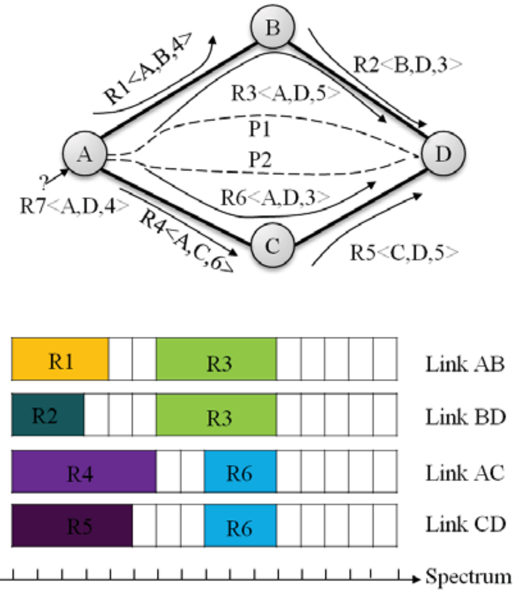


Fig. 2: An example of spectrum fragmentation issue

past work proposes a method referred to as *Single Slot on the Grid Approach* illustrated in Figure 1 [3]. In this approach, the frequency slots are based on the ITU-T fixed grids, i.e., the central frequency is allocated at 193.1THz. The width of a frequency slot depends on the specific transmission systems. In this example, one frequency slot is 12.5GHz. Upon receiving a connection request, a group of frequency slots, usually consecutive in frequency domain, are assigned according to its bandwidth requirement.

2) Spectrum Fragmentation and Multipath Routing: While simple to compute and setup, single path routing in the routing and spectrum assignment can fragment the spectrum and lead to inefficiency, also referred to as *spectrum fragmentation issue* [2]. An example is shown in Figure 2. A traffic demand is defined as $R_n(S, D, T_r)$, where S, D and T_r are source, destination, and the number of required sub-carriers, respectively. The spectrum on each fiber is assumed to be divided into 16 sub-carriers and connection requests arrive in time order, i.e., traffic demand R_n arrives after R_{n-1}. The used spectrum is marked with shaded slots (e.g., R_1 to R_6), whereby size of the guard-band is assumed to be 2 sub-carriers. A group of consecutive frequency slots that are available after spectrum allocation for $R_1, R2, ..., R_6$ is referred to as *spectrum fragment (SF)*. In this scenario, the traffic demand R_7 at node A is rejected, since it is not possible to allocate 4 consecutive sub-carriers. In fact, all traffic demands requesting more than 3 sub-carriers will be blocked under the current network condition. This phenomena is particularly pronounced under dynamic traffic scenarios. However, two spectrum paths, i.e., P_1 and P_2, can be set up in parallel for R7 using multipath routing.

B. Preliminary

An elastic optical path network is represented as $G(V, E)$, where V is the set of nodes and E is the set of fiber links. The spectrum on each fiber link can be divided into $|F|$ slots and placed in an ordered set $F = \{f_1, f_2, ..., f_N\}$. Length of link $e \in E$ is denoted as LD_e. The length of a spectrum path is the sum of length of all fiber links it traverses, which is defined as $pd_p = \sum_{e \in p} LD_e$. The modulation formats that can be supported by the network are denoted as m_k, $m_k \in \mathcal{M}$. For each modulation format, there exists a maximum transmission distance, denoted as L_{m_k} [3]. A modulation format m_k can be applied to a spectrum path p, only if $pd_p \leq L_{m_k}$. Otherwise, a modulation format with lower modulation level has to be used. A connection demand is represented as $R(S, D, C)$, where S, D and C are source, destination, the required transmission data rate, respectively. The number of sub-carriers that are required by a request R depends on the used modulation format. Assume the bit rate per symbol of a modulation format m_k is denoted as b_{m_k}, then the number of sub-carriers (N_{sub}) for a traffic demand can be calculated as follows:

$$N_{sub} = \lceil C/(b_{m_k} \cdot f_{slot}) \rceil \qquad (2)$$

where C is the size of traffic volume and f_{slot} is spectrum width of a frequency slot, respectively. The number of frequency slots assigned as guard-band between adjacent spectrum paths is denoted as GB. When multiple spectrum paths on diverse fibers are used, the maximal allowable differential delay is denoted as DD, which is determined by the alignment capability of the network, e.g., $\pm 125us$ as suggested in ITU-T G.709 [5]. Finally, we assume that the power injected in transponders for each channel is constant. It is due to the fact that modifying power individually for each channel can affect the gain and penalty of other channels which share the same optical amplifier in the same fiber link [8]. Therefore, the data transmission rate of each sub-carrier channel only depends on the modulation level in this paper, i.e., bits per symbol.

To ease understanding of the proposed heuristics, we first clarify the terminology as follows:

- Spectrum path (p): A spectrum path is composed of one or multiple consecutive sub-carriers between source and destination, with consideration of spectrum continuity constraint. Each spectrum path calculated for a connection demand is an element of a path set, denoted as $\mathcal{P}$.
- Fiber level path (fp): A fiber-level path is composed of a sequence of fiber links between source and destination. It can contain one or multiple spectrum paths. Each fiber-level path calculated for a connection request is an element of a set, denoted as $\mathcal{FP}$.
- Spectrum fragment (SF): A spectrum fragment on a fiber link is a one or multiple consecutive sub-carriers which are not used by the existing spectrum paths. A spectrum fragment is typically formed due to spectrum continuity constraint or due to the dynamic tear-down of spectrum paths as shown in Figure 2.

C. Heuristics with and without pre-computed paths

1) Without pre-computed paths (Heuristic-I): The first heuristic algorithm is shown in Alg.1. It starts from computing the shortest fiber-level path $\tilde{fp}$ with available continuous spectrum. It then assigns a best modulation format, e.g., m_j, depending on the length of $\tilde{fp}$. The modulation format is assigned by comparing the path length with the reference distance of available modulation formats in $\mathcal{M}$. For instance, if $Lm_{j-1} < pd_{\tilde{fp}} \leq L_{m_j}$, m_j is the best option for spectrum paths on the fiber-level path $\tilde{fp}$. The required number of sub-carriers can be calculated based on the bit rate of the modulation format m_j, as shown in Eq.(2). If there are enough sub-carriers to support the bandwidth requirement, a single path solution is found. Otherwise, it goes on aggregating available spectrum fragments on $\tilde{fp}$. If available resource on a single fiber-level path cannot support the connection demand, the algorithm reserves all available bandwidth on $\tilde{fp}$ and computes the next shortest path in the network. If the differential delay between the new path and any spectrum paths that have been reserved is larger than the predefined value DD, the computation is terminated. The connection demand is rejected in this case. Assume the total number of frequency slots on link e is F and maximum K paths can used, the complexity of Alg.1 is in $O(|V^2| \cdot F \cdot K)$.

2) With pre-computed paths (Heuristic-II): The second algorithm decomposes the problem into two sub-problems, namely, 1) multipath routing and modulation assignment; and 2) spectrum assignment, as shown in Alg.2. The Step-I in Alg.2 is to find a set of fiber-level paths and sort the paths in the increasing order of delay. We assume that maximum K fiber-level paths can be used, and all pre-computed paths are placed in $\mathcal{FP}$, where $|\mathcal{FP}| \leq K$. The routing starts from source node S are placed in a set, namely $\mathcal{S}$, which is ordered in an increasing order of delay. $\mathcal{S}$ is initialized with all outgoing links from source S . The path with shortest delay in $\mathcal{S}$ is selected, denoted as fp. It is extended to all the nodes that connected to the sink node of fp, denoted as $destination(fp)$. The path set $\mathcal{S}$ is updated with new paths. It stops till the shortest path in $\mathcal{S}$,i.e., fp, reaches destination node D. The path fp is placed into the set $\mathcal{FP}$ which will be used as input in spectrum assignment stage. The algorithm then checks the shortest path in current $\mathcal{S}$ and repeats the same procedure. It stops when there is no more available path or K paths have been found. Finally, the algorithm compares the length of each path p_k and assigns a best modulation format m_j, denoted as $p_k(m_j)$. In the worst case scenario, the Step-I of Alg.2 has to visit all the nodes in the network to find a path fp between S and D. Assume the maximum node degree in the network is $\{Deg(V)\}$, the complexity of Step-I in Alg.2 is in $O(|V^2| \cdot Deg(V) \cdot K)$.

Step-II of Alg.2 is for spectrum assignment. It starts from searching available spectrum slots on the shortest path in $\mathcal{FP}$. At this stage, we consider bandwidth requirement constraints

Algorithm 1: Heuristic-I: Multipath Routing with Shortest-Path-First Spectrum and Modulation Assignment

```
Input: G(V,E), DD, M, R(S,D,C)
Output: Spectrum path(s) P with assigned modulation format
reservedBw = 0; P = ∅
while (reservedBw ≤ C) do
    Compute a shortest fiber-level path f̃p with available
    continuous spectrum;
    if ( ∀p ∈ P, pd_f̃p − pd_p > DD ) then
        break;
    end
    while (Spectrum available on f̃p) do
        Compute the widest spectrum path p̃ on f̃p with x̃
        consecutive sub-carriers;
        if No Spectrum Path Found on f̃p then
            break;
        end
        //assign the best modulation format;
        if (Lm_{j−1} < pd_f̃p ≤ L_{m_j}) then
            Assign m_j to path fp; m_j ∈ M
        end
        Compute bandwidth b̃ for the spectrum path p̃ with
        sub-carriers x̃ available in M;
        reservedBw +=b̃;
        Mark subcarriers in selected in p̃ as reserved;
        Add spectrum path p̃ to P;
    end
end
return P;
```

Algorithm 2: Heuristic-II: Spectrum and Modulation Assignment with Pre-computed Paths

```
Input: G(V,E), K, R(S,D)
Output: FP and P
StepI: Multipath routing and modulation assignment
Parameters: S as an ordered (via delay) set of paths starting
from source S;
while (|FP| ≤ K) do
    while destination(fp) ≠ D do
        Select min-delay path fp from S
        for all nodes v′ connected to destination(fp) do
            if (v′ not traversed in fp) then
                create fp′ by extending fp to v′
                add fp′ to S
            end
            Put fp into FP
            Remove fp from S
        end
    end
end
for k = 1 to K, fp_k ∈ FP do
    if ((Lm_{j−1} < pd_f̃p) then
        Assign m_j to path fp_k, i.e., fp_k(m_j)
    end
end
StepII: Spectrum assignment
for k = 1 to K, fp_k ∈ FP do
    Sort all available spectrum paths in the increasing number
    of delay;
    and put in path set P
    N = |P|
end
for k = 1 to N do
    if pd_{p_{k+1}} − pd_{p_k} ≤ DD then
        F+ = F_{p_k}
        if F · b_{m_j} ≥ C then
            Return spectrum paths and break;
        end
    end
end
```

as defined in Eq.(2). All available spectrum paths on fiber-level paths in $\mathcal{FP}$ are identified and sorted in the increasing number of delay in P. In this step, it is important to consider the differential delay issue due to the diversity of the fiber-level paths involved. It starts from the shortest path and compare the differential delay between p_k and p_{k+1} with the maximum allowable differential delay. If it meets the differential delay constraint, the available spectrum fragments will be accumulated and the algorithm moves on to the next round. A solution is found when bandwidth requirement is satisfied. In the worst case scenario, Step-II of Alg.2 has to check all the sub-carriers over all fiber links. Hence, the computational complexity of spectrum assignment stage is in $O(|K| \cdot |F| \cdot |E|)$.

IV. Performance Evaluation

We evaluate the proposed algorithms in Janos-us network with 24 nodes and 84 links, as shown in Figure 3 [9]. The number of sub-carriers per link is 128 and the spectrum width per frequency slot is 12.5GHz. For practical reasons, only four modulation formats are considered, i.e., on-off with 1 bit/symbol, QPSK with 2 bits/symbol and 16QAM with 4 bits/symbol as well as 64QAM with 8 bits/symbol, with the reference distance of $8000km$, $4000km$, $2000km$ and $1000km$, respectively. Note that the reference distance of each modulation format is based on assumptions. Connection demands arrive following a Poisson process and are uniformly distributed among all nodes.

We assume that connection demands are extremely high in order to evaluate multipath routing algorithms. In the context of the today's high-speed Ethernet networks this would be equivalent of any value between 100Gbps and 120Gbps. The maximum allowable differential delay is set to be $250us$. The network load A (in Erlang) is defined as $u * h$, where u is connection arrival rate and h is the mean connection holding time. In our study, the mean inter-arrival time is $1s$ and holding time is varying to achieve different network load. In addition, we also show the performance of single path routing algorithm (SP) based on shortest-path-first. For a fair comparison, distance-adaptive modulation assignment is also applied in the single path approach.

Figure 4 shows the blocking probability of single- and multipath routing, with different guard-band sizes, i.e., $GB = 1, 2$. As it can be seen, the proposed multipath routing algorithms result in a lower blocking probability comparing with single path routing only. The Heuristic-II has better performance than Heuristic-I due to the fact that an optimal solution can be found. Figure 4 also shows that the number of sub-carriers

Fig. 3: Janos-US network topology [9] under study with 26 nodes and 84 links

required as guard-band can affect the performance of all routing and spectrum assignment algorithms. A larger guard-band leads to a higher blocking probability. As shown in Figure 4, the blocking probability with GB=2 is an order of magnitude larger than that of GB=1. The advantage of multipath routing is especially pronounced when network load is high. Around 1% reduction of blocking is observed with both multipath algorithms with GB=2, comparing with single path approach.

The next set of study focuses on spectrum efficiency. In Figure 5, it can be seen that using multipath routing does not significantly increase the average spectrum usage on links, even when the guard-band size is different, which makes it highly spectrum efficient. For instance, when GB=1, both single and multipath routing approaches consume average 15% spectrum resource is used to set up spectrum paths when network load is 70Erlang, while around 25% spectrum resource is consumed by spectrum paths at 120Erlang, as shown in Figure 5(a). The results in Figure 4 and Figure 5 show that using multipath routing can improve spectrum efficiency, since it can support more connections while consuming similar amount of spectrum resource as single path routing.

One concern of using multipath routing in elastic optical networks is that using more paths may lead to higher spectrum consumption on guard-band. Figure 6 shows the average percentage of spectrum on link e used by guard-band, where only slight increase has been observed when network load is high and guard-band requirement is large. As shown in Figure 6(b), when network load is larger that 95Erlang, the proposed algorithms consume more spectrum resource on guard-band. The important phenomenon observed in this study is that guard-bands in either single path routing and multipath routing approaches consume a substantial number of frequency slots (Figure 5(b)), which is a key issue in flexi-grid networks. To mitigate this issue, on one hand, more advanced optical network elements, such as filtering, transceivers etc, are required to reduce the required guard-band to isolate the adjacent spectrum paths. On the other hand, efficient routing and spectrum assignment algorithms are a workaround solution, such as the proposed multipath routing approaches.

Finally, it should be noted that guard-band size is a critical

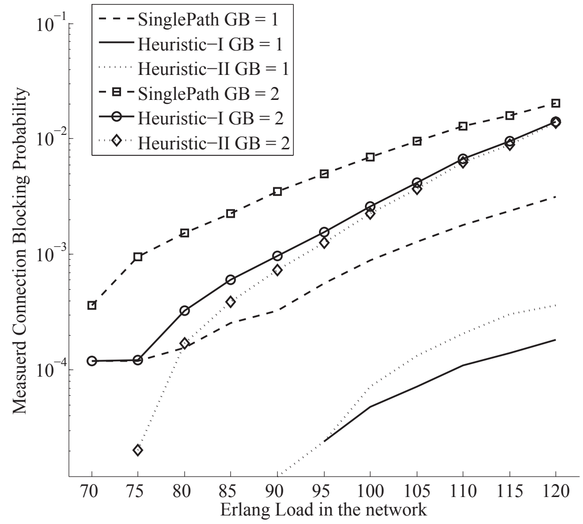
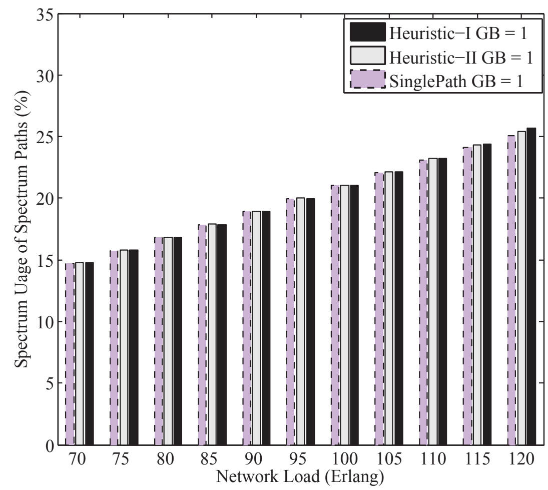
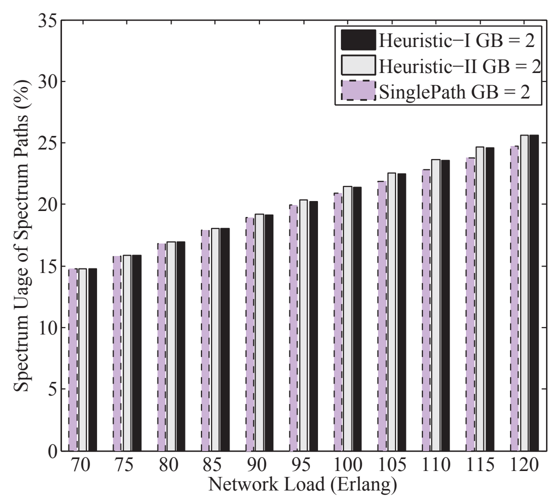


Fig. 4: Blocking probability with guardband (GB=1,2)

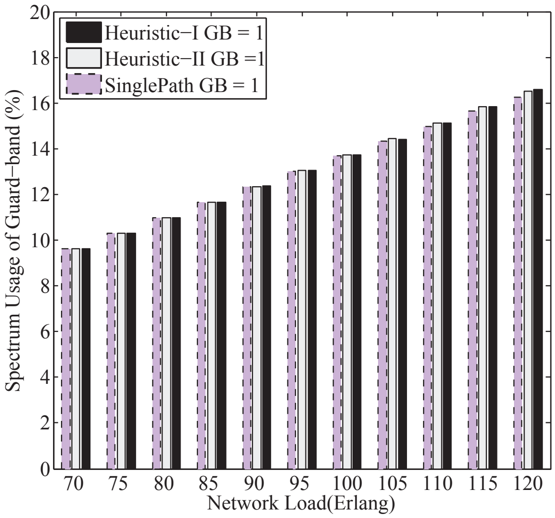


(a) GB=1

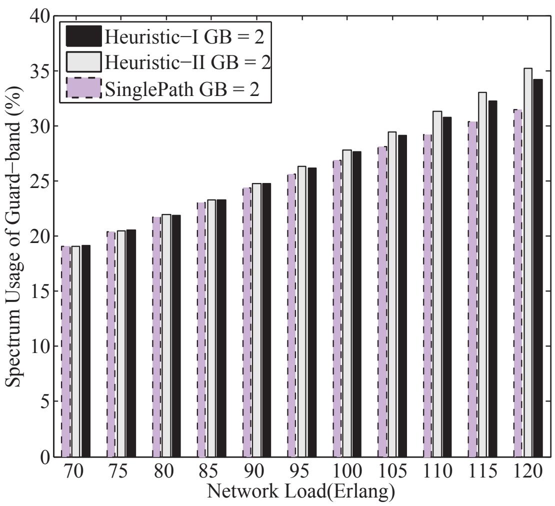


(b) GB=2

Fig. 5: Spectrum used by spectrum paths



(a) GB=1



(b) GB=2

Fig. 6: Spectrum used by guard-band

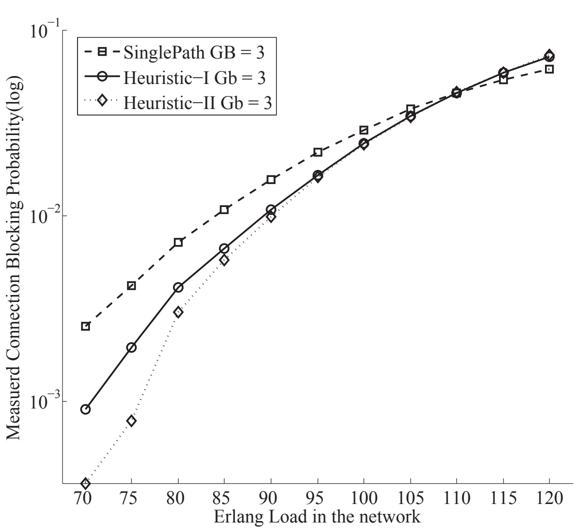


Fig. 7: Blocking probability with guardband (GB=3)

factor which should be designed with care to fully benefit from multipath routing. As shown in Figure 7, using multipath can reduce the blocking probability when 3 sub-carriers are used as guard-band under certain network load, i.e., 110Erlang. When network load is higher than 110 Erlang, multipath routing approaches result in a higher blocking comparing with single path routing due to its slightly higher need for guard-bands. From this study, we conclude that multipath routing is more suitable for the network requiring smaller guard-band, i.e., in support of lower speeds of individual connections jointly setup in multipath routes.

V. Conclusion

Until now, studies on routing and spectrum allocation in elastic optical networks have been focused on single path routing and uniform modulation formats, where spectrum fragmentation remains an open issue. In this paper, we proposed novel algorithms for multipath routing and spectrum assignment with consideration of distance-adaptive modulation assignment and analyzed its effectiveness. The numerical results showed that using multipath routing can reduce the blocking probability while consuming comparable spectrum resource as single path routing, which makes multipath routing highly spectrum efficient. We showed that spectrum resource consumed by guard-band is a critical factor, where multipath routing can be a workaround solution. We conclude that multipath routing is beneficial for elastic optical networks with small guard-bands.

VI. Acknowledgment

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