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Impairment-Aware Routing in Translucent Spectrum-Sliced Elastic Optical Path Networks

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Abstract—**Spectrum-sliced elastic optical path (SLICE) technology offers a more flexible bandwidth allocation in optical networks than wavelength division multiplexing. It allows different connections to be served via different modulation formats. However, as with any optical network, the optical signal may be susceptible to signal impairments, especially when the signal traverses over long distances. The degree of impairment may differ per modulation type, but in any case must be taken into account. If impairment levels get too high, the signal needs to be regenerated by regenerators placed selectively (due to cost considerations) inside the network.**

In this paper we study the impairment-aware dynamic routing and subcarrier allocation problem in translucent SLICE networks. We propose an impairment-aware routing algorithm that tries to balance traffic flows evenly across the network to reduce the blocking probability. We consider two cases, namely (1) a modulation will be selected that is used by the entire connection, and (2) the modulation can be changed during regeneration at regenerator nodes on the path.

I. Introduction

In WDM technology, the capacity of a fiber is divided into several non-overlapping wavelength channels and each wavelength channel has a fixed-size frequency so as to be able to transport data independently. These wavelength channels make up lightpaths that are used to establish optical connections that may span several fiber links. However, traffic between a pair of nodes may not fill up the available bandwidth of a lightpath. In order to efficiently utilize the available bandwidth, several independent traffic streams can be aggregated to share the capacity of a lightpath, which is known as traffic grooming (e.g., see [1]). However, it only makes sense to groom the new request onto existing lightpaths that have the same source and/or destination, otherwise extra wavelength channels should be set up to connect the existing lightpaths. Traffic grooming may therefore induce some inefficiency in capacity utilization.

In order to facilitate a more efficient capacity utilization, a spectrum-sliced elastic optical path (SLICE) architecture was proposed in [2]. In this kind of network, the capacity of a fiber link is divided into a fixed number of low data rate transporting units, which are called subcarriers. Unlike in WDM networks where all the wavelength channels are separated by a guard band in the frequency domain to prevent interference, the subcarriers in SLICE can partially overlap in the frequency domain with the aid of OFDM technology. In this context, SLICE transports each traffic request by allocating just enough subcarriers according to its capacity requirements. However, SLICE has its own characteristics: on the one hand OFDM requires that the allocated subcarriers have to be consecutive in the spectrum domain and fiber links on a path should use the same consecutive slots. On the other hand, to avoid interference effects between optical paths, appropriate spectrum separation, implemented by spectrum guard bands (guard carriers), is required if two spectrum paths overlap or traverse the same fiber link. Routing and Wavelength Assignment (RWA) is a typical and fundamental problem in WDM optical networks and the analogous problem in SLICE is referred to as the Routing and Subcarrier Allocation (RSA) problem. Although the RWA and RSA problems are related, one often cannot directly use existing RWA algorithms [3], [5]. One of the distinguishing features comes from the modulation types.

BPSK is the modulation format with the highest quality of transmission (QoT). When the actual distance of a path is longer than the QoT threshold of a modulation format permits the signal should be regenerated. We refer to a node that has regeneration capability as a regenerator node. Regenerator nodes can restore the signal to its original strength. The Impairment-Aware Path Selection (IAPS) problem aims to find a path that does not violate the QoT threshold. We do not address the impairment factors that affect QoT and only consider that the signal's transmission reach is related to the modulation used and that, when a signal traverses a longer distance than the selected modulation format's acceptable transmission reach, it needs to be regenerated. After being regenerated the signal can again travel the maximum transmission distance. We refer to this maximum distance as the impairment constraint.

A. Outline

In this paper, we propose an impairment-aware routing algorithm for translucent SLICE networks. The remainder of this paper is organized as follows. Section II defines the problem and discusses how to find consecutive subcarriers. An impairment-aware algorithm for SLICE networks is proposed in Section III. Section IV provides our simulation results. Section V presents related work and Section VI concludes

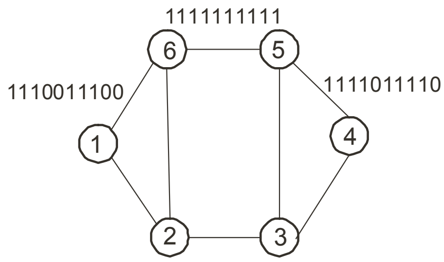

Fig. 1. Example allocation of subcarriers

the paper.

II. Problem Definition and Spectrum Allocation

A. Problem definition

Given is a network represented by $G(\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ represents the set of N nodes and $\mathcal{L}$ denotes the set of L links. A number of nodes have regeneration capability. $d(i, j)$ denotes the physical distance between nodes i and j. The M available modulation formats are represented by $M_i, i = 1, 2, ..., M$. We use $D(M_i)$ to denote the transmission reach for each modulation format and $R(M_i)$ to denote the bit rate for a single subcarrier in each modulation format. The single bit per symbol modulation (BPSK) capacity per subcarrier is denoted by C, so the capacity per subcarrier for QPSK is equal to $2C$, etc. We define F as the total number of subcarriers in one fiber link and assume that each subcarrier has the same frequency span.

Given a request, represented by $r(s, t, b)$ where s and t are the source and destination nodes, and b represents the requested data rate, the problem is how to select a feasible path from s to t and allocate subcarriers by using an appropriate modulation format, such that the data rate and impairment constraints are obeyed. We refer to this problem as Impairment-Aware Routing and Subcarrier Allocation (IARSA).

Theorem 1: The IARSA problem is NP-hard.

Proof: The IARSA problem without subcarrier allocation is equal to the NP-hard impairment-aware path selection problem presented in [8], from which the proof for the hardness of IARSA follows. ■

Since the IARSA problem is NP-hard, in this paper we will focus on developing a heuristic solution.

B. Subcarrier allocation

We assume that all the links have the same amount of subcarriers and use 1 to denote that a subcarrier is free and 0 that it is used. In Fig. 1 each fiber has 10 subcarriers and for link $(1, 6)$, for example, the subcarriers 1, 2, 3, 6, 7, 8 (we count from left to right) are free. Assume we want to use path $1-6-5-4$ to accommodate a traffic request $(1, 4, 2)$ whose source and destination nodes are 1 and 4, respectively, and which is requesting 2 subcarriers. The guard carrier's capacity is assumed to be 1 subcarrier. An *and operation* results in 1110011100 and indicates that the subcarriers 1 to 3 and 6 to 8 among these 3 links are free. We take the convention that subcarriers are first allocated and then the guard carrier is appended to the last allocated subcarrier. Considering the requested bandwidth, it can be seen that these 3 links are able to accommodate this traffic by allocating either subcarriers indexing from 1 to 2, putting the guard carrier at index 3 or subcarriers indexing from 6 to 7, putting the guard carrier at index 8.

III. Impairment-Aware Routing Algorithm

A. Algorithm specification

We use

$$w(u, v) = \frac{\beta}{A(u, v)} \quad (1)$$

to reflect the link utilization in proportion to the requested bandwidth, where (u, v) represents the link between nodes u and v, β denotes the requested number of subcarriers and $A(u, v)$ indicates the number of free subcarriers. If $w(u, v)$ is large this implies that allocating the requested subcarriers would take up a large portion of the existing free subcarriers, which might create a bottleneck. We use $w(u, v)$ as our link weight, although other measures for weight could be used as well, as studied in Sec. IV.B.

Our aim is to find the shortest feasible path, where feasibility is determined by the availability of common free subcarriers along the path and by the impairment levels and use of regenerators. By using the bit string representation of the subcarriers and using the *and operation*, the availability of subcarriers can be calculated per visited node. Similar as in WDM networks, where the signal can be assigned a different wavelength at converter or regenerator nodes, the allocated subcarriers might also be changed at a regenerator node. In our algorithm we first assume that each traversed regenerator node will regenerate the signal and later select only those truly needed. The following parameters are used:

$sus[i]$: the parent node of node i.

$cost[i]$: the minimum path cost in terms of Eq. 1 found so far from source to node i.

$dist[i]$: the impairment slack in terms of distance when a signal arrives at node i. We set this value to be the maximum transmission distance of the corresponding modulation format when node i is a regenerator node.

$com[i]$: the bit string representation of the available subcarriers on the path from source to node i.

Algorithm 1 describes the main body of the algorithm. Once a request $r(s, t, b)$ arrives the algorithm first allocates weights to the links according to Eq. 1 and based on different modulation formats. If in BPSK each subcarrier carries C Gbps, then in QPSK each subcarrier contains $2C$ Gbps, and so on for other modulation formats. Hence, if the request r asks for b Gbps bandwidth, for BPSK it needs $\beta = \lceil \frac{b}{C} \rceil$ subcarriers, while for QPSK it needs $\beta = \lceil \frac{b}{2C} \rceil$ subcarriers. After allocating the weights we run Algorithm 2, which basically is a version of Dijkstra's shortest paths algorithm that includes some extra constraints in the relaxation. Steps $4-5$ in Algorithm 1 imply that if none of the modulation

Algorithm 1 $LARA(G, r)$

1: **for** $i = 1, \ldots, M$ **do**
2: Allocate link weights
3: $M[i] \leftarrow$ ModifiedDijkstra(G,r,i)
4: **if** All $M[i]$ equal NULL **then**
5: Block request
6: **else**
7: Return the path P and modulation format m corresponding to Min($M[i]$)
8: Call $GraphAdjust(G, r, P, m)$ to allocate subcarriers
9: **end if**
10: **end for**

Algorithm 2 $ModifiedDijkstra(G, r, m)$

1: For all nodes $walked[]$ is set to be FALSE
2: **while** $walked[t]$ is FALSE **do**
3: Select $u \leftarrow Min(cost[i])$ //among nodes i for which $walked[i]$ is FALSE
4: **if** $Min(cost[u])$=infinity **then**
5: Return NULL
6: **end if**
7: $walked[u] \leftarrow TRUE$
8: **if** u is the source node || u is a regenerator node **then**
9: Set $com[u]$ to be all 1 in its bits
10: $dist[u] \leftarrow D[m]$
11: **else**
12: Update $com[u]$ via an and operation between $com[sus[u]]$ and the bit string of link $(sus[u], u)$
13: $dist[u] \leftarrow dist[sus[u]] - d(u, sus[u])$
14: **end if**
15: **for** each unwalked neighbor v of u **do**
16: **if** $cost[v] > cost[u] + w(u, v)$ && $d(u, v) <= D[m]$ && enough subcarriers are present && $dist[u] >= d(u, v)$ **then**
17: $cost[v] \leftarrow cost[u] + w(u, v)$
18: $sus[v] \leftarrow u$
19: **end if**
20: **end for**
21: **end while**
22: return $cost[t]$

formats can provide a path then the request will be blocked, otherwise in step 8 the path with the lowest weight will be selected and Algorithm 3 is called to adjust the topology and assign the subcarriers and regenerators.

To understand Algorithm 3, let us use an example to explain how to partition just enough segments in one path according to the signal strength in terms of transmission distance. In Fig. 2, we assume that the maximum optical reach is 3000 km and the path from node 1 to node 5 in the figure is the final calculated routing path. In this example nodes 2 and 3 are the regenerator nodes, and the other 3 nodes do not have

Algorithm 3 $GraphAdjust(G, r, P, m)$

1: Partition the path into s segments based on the set R of regenerator nodes on the path.
2: Calculate the physical distance of each segment and record them (via $seg[i]$) in the $|R|$ regenerator nodes and destination node. $dist[i]$ indicates the remaining impairment slack in terms of distance at node i and $dist[source] = D[m]$
3: **for** each regenerator node i in set R **do**
4: $dist[i] \leftarrow dist[sus[i]] - seg[i]$
5: **if** $dist[i] < 0$ || not enough subcarriers between last marked regenerated node and node i **then**
6: Mark node $sus[i]$ to regenerate the signal
7: $dist[i] \leftarrow D[m] - seg[i]$
8: **end if**
9: Partition the path into segments according to the selected regenerator nodes
10: Allocate subcarriers in each segment and set these bits to 0 in the corresponding links
11: **end for**

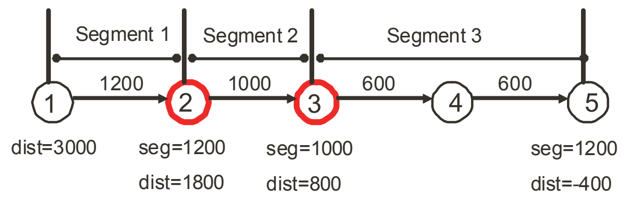

Fig. 2. Illustration of Algorithm 3

regeneration capability. Each link has a certain given physical distance and below each node we list the variables used in Algorithm 3. Although 3 segments exist, $dist[5] = dist[3] - seg[5] = -400$ indicates that only node 3 needs to use its regeneration capability to restore the signal. In our Modified Dijkstra algorithm, we first assume that all the regenerators restore the signal, so the array com is updated to all 1s at each regenerator node. In this sense when Algorithm 3 partitions the segments for a selected path, if one regenerator is skipped and hence treated as a normal node, we also need to check whether the subcarrier allocation constraint is obeyed. In this example, only when link $(1, 2)$ and link $(2, 3)$ have enough common subcarriers to accommodate the traffic, node 2 does not have to regenerate the signal and we only let node 3 restore the signal.

The complexity of the whole algorithm is dominated by M times the complexity of Algorithm 2. Algorithm 2 is essentially Dijkstra's shortest algorithm where the relaxation procedure in step 15 also needs to check in $O(F)$ time whether there are enough subcarriers to accommodate the traffic. Therefore, the total complexity of the algorithm accumulates to $O(MN\log(N) + MFL)$.

B. Regenerator node can change modulation format

According to Simmons [9], in WDM optical networks a regenerator node can be implemented by either back-to-back

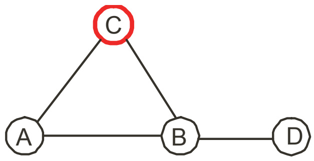

Fig. 3. Example

transceivers or via regenerator cards. Since the transceivers in SLICE can change the modulation format, by choosing back-to-back transceivers, the regenerators could also have the capability of changing the modulation format. We propose an auxiliary graph to represent this case and on which our ModifiedDijkstra algorithm can be executed. The auxiliary graph has $M + 1$ layers, where M is the number of available modulation formats. Each modulation layer represents a modulation format, with proper weight allocation and transmission reach. An additional virtual layer is used to host the source and destination. This layer only contains nodes but no links between those nodes. We draw vertical links between the nodes in the virtual layer and their counter parts in all the other modulation layers. Links to regenerator nodes are called regenerator links, and vertical links from/to the source or destination are called virtual links. These two types of links are assigned a weight 0 (but could also be assigned a small weight to discourage to often switch between layers). Algorithm 3 then needs to be modified to account for the proper modulation format (layer). Since each layer represents one modulation, each subpath in one certain layer corresponds to one segment. The subcarriers of subpaths are allocated in each layer according to the different modulation formats. For example, in Fig. 3 node C is the only regenerator node and we want to route traffic from node A to node D. The corresponding auxiliary graph is shown in Fig. 4 where we assume that there are only two modulation formats (e.g., BPSK and QPSK).

IV. Simulations

We use the USANet network shown in Fig. 5. We assume each fiber link has 256 subcarriers and that the capacity of a guard carrier is equal to 1 subcarrier. Following Christodoulopoulos *et al.* [5], we assume each subcarrier spacing is 5 GHz, so for BPSK and QPSK, each subcarrier can carry 2.5 Gbps and 5 Gbps data, and their respective acceptable transmission reach is 3000 km and 1500 km. We only consider these 2 modulation formats since other modulation formats (8-QAM, 16-QAM,...) typically have a transmission reach of less than 750 km which is less than most of the link distances. We let the even numbered nodes have sufficient regenerating capability. For comparison purposes, 2 other algorithms are presented. The first one only adopts a single modulation format and uses the distance as link weight. We use SP-BPSK and SP-QPSK to represent this algorithm for the respective modulation format. The second algorithm is similar to our proposed algorithm (in the sense that it can

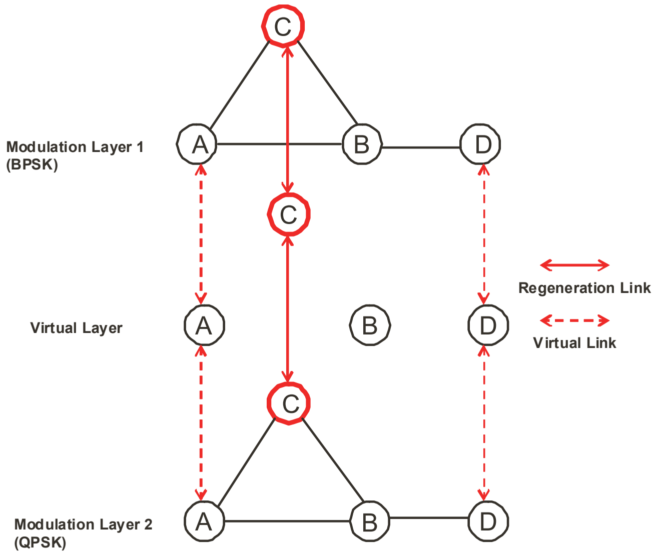

Fig. 4. Auxiliary graph

choose the modulation) except that it does not take our load-aware weight into account and only uses the distance. We call this algorithm LURA (Load Unaware and Regenerator Aware) and use LARA (Load Aware and Regenerator Aware) to refer to our proposed algorithm. Correspondingly, LARA-M and LURA-M are used to represent the case when after being regenerated, the modulation format of the signal can be changed by the regenerator node.

A. Performance evaluation

We vary the number of connection requests from 100 to 1000, and for each request, the source and destination nodes are randomly generated, and the requested bandwidth ranges from 1 to 10 Gb/s. The blocking probability is shown in Fig. 6. It can be seen from the figure that LARA-M and LURA-M can accommodate all requests. When modulation cannot be changed at regenerators, LARA outperforms the alternatives. LARA and LURA adaptively choose a modulation format so they can accommodate more traffic compared to a single modulation BPSK and QPSK (SP-BPSK and SP-

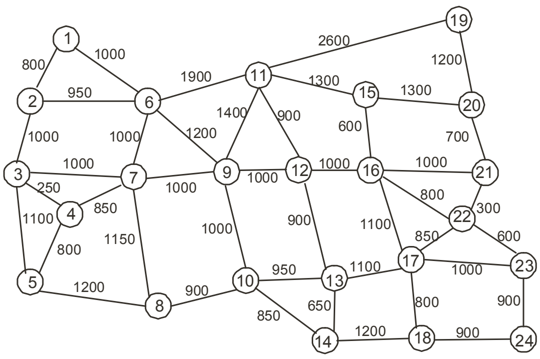

Fig. 5. USANet including link distances in km

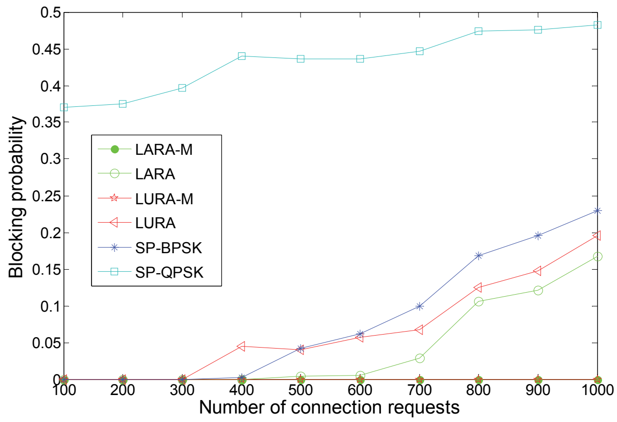

Fig. 6. Blocking probability when even numbered nodes have regeneration capability

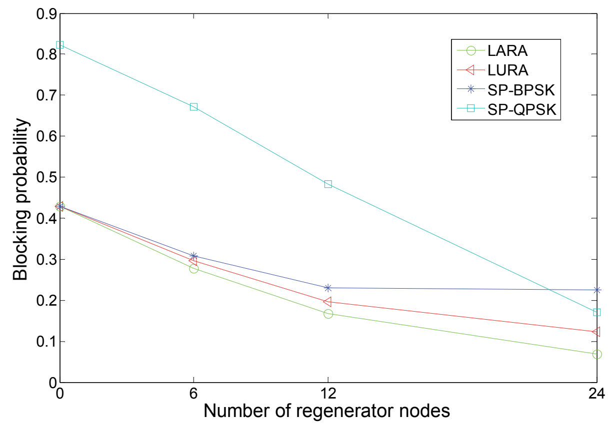

Fig. 7. Blocking probability for different numbers of nodes with regeneration capability

QPSK). Furthermore, SP-QPSK behaves worst because it has a shorter transmission reach than BPSK. BPSK, on the other hand, consumes more subcarriers than QPSK. Our choice of weight makes LARA outperform LURA. In the following we proceed with the hardest case in which the regenerator nodes cannot change the modulation.

Under the same simulation setup as for Fig. 6, Fig. 7 gives the blocking probability for different numbers of regenerator nodes. For all algorithms the blocking probability drops with an increase in regenerator nodes. When all nodes can regenerate, SP-QPSK has a lower blocking probability than SP-BPSK since the shorter transmitting distance with QPSK is compensated by the regenerators and SP-QPSK uses fewer subcarriers.

B. Weights allocation

In this section we will evaluate the effect of weight allocation. Although load balancing can circumvent bottlenecks, it might come at the expense of having longer paths, which may lead to a higher blocking probability. Thus it is important to strike a balance between load balancing and path length. The cost of the path returned by our algorithm can be represented as

$$\text{cost} = \min_{P} \left(\sum_{(u,v)\in P} \frac{\beta}{A(u,v)} \right) \quad (2)$$

In order to make a comparison, we list 4 other cost functions of existing state-dependent adaptive routing algorithms in Table 1, where $A(P)$ reflects the number of common free subcarriers on the path P, and $h(P)$ is the hopcount of path P. All 4 algorithms precalculate a fixed number of routes between each node pair and select one of them that has the minimum (maximum) cost value according to their cost function. We use their cost function for weight allocation in our proposed algorithm. Specifically, for WLCR and LLR, since their objective value is the maximum value whereas our algorithm needs to find the minimum cost value, we convert their cost function and use $\frac{\sqrt{h(v)})}{C(u,v)}$ and $\frac{1}{A(u,v)}$ as weight function on link (u, v) and run our algorithm with them. For the CAR and WSP, we remain their original cost function as our weight allocation, namely $\frac{F-A(u,v)}{F*h(v)}$ and $\frac{F-A(u,v)}{F}*h(v)$ as weight function on link (u, v) where $h(v)$ is the minimum hopcount from source to node v. We use the same simulation setup as explained for Fig. 6. Fig. 8 shows the results from the comparison, where LARA achieves the lowest blocking probability. We believe that an underlying reason may be that it is difficult to explicitly formulate an optimal relationship between load balancing and path length. The weight functions of the algorithms in Table 1 do not reflect the ratio between requested subcarriers to the total available subcarriers in each link as our algorithm. They therefore cannot present the actual loading status in each fiber link compared to our algorithm, which results in higher blocking probability. On the other hand, our weight allocation tries to strike a balance between load levels and path lengths (even though the path length is not explicit in Eq. 1).

TABLE 1 Compared cost functions

Algorithm	Cost function	Value
Congestion-Aware Routing (CAR) [10]	$\frac{F-A(P)}{F} * \frac{1}{h(P)}$	min
Weighted Least-Congestion Routing (WLCR) [11]	$\frac{A(P)}{\sqrt{h(P)}}$	max
Weighted-Shortest Path Strategy (WSP) [12]	$\frac{F-A(P)}{F} * h(P)$	min
Least Loaded Routing (LLR) [13]	$\min\left(A(P)\right)$	max

V. Related Work

Wang *et al.* [3] [6] comprehensively analyze the static RSA problem in ring and mesh topologies. They first prove that the RSA problem is NP-complete, and subsequently use Integer Linear Programming (ILP) to minimize the maximum subcarrier index among all the fiber links or to minimize the number of allocated subcarriers over all the fiber links. In addition, two heuristics are proposed, namely the Shortest Path with Maximum Spectrum Reuse (SPSR) and the Balanced Load Spectrum Allocation (BLSA) algorithms.

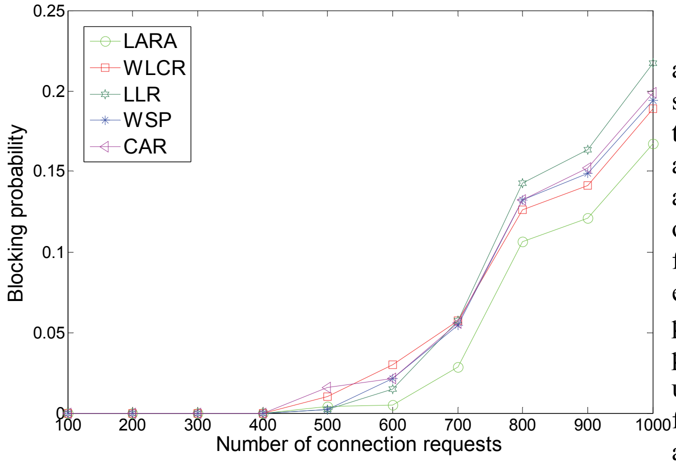

Fig. 8. Blocking probability when different weight functions are used

Zhang *et al.* [4] introduce traffic grooming to OFDM-based networks, meaning that several spectrum paths can share the same guard carrier if they have the same source or (and) destination. They set up a MILP (mixed ILP) to represent this case. The numerical examples reveal that compared to the non-traffic-grooming scheme, where each request is accommodated by one guard carrier, the traffic grooming scheme can save up to 24% in bandwidth.

Christodoulopoulos *et al.* [5] jointly consider Routing, Modulation Level, and Spectrum Allocation (RMLSA) and respectively propose joint and decomposed ILPs to solve the RMLSA problem. They also propose a greedy heuristic to sequentially accommodate the traffic requests. The simulation results verify that by changing modulation levels, OFDM-based optical networks can achieve much higher spectrum utilization than typical WDM optical networks.

Wan *et al.* [7] proposed three algorithms for routing dynamic traffic in SLICE:

- k-shortest path algorithm that precalculates k shortest paths and chooses one of them to accommodate the traffic request.
- An algorithm similar to Dijkstra's shortest paths algorithm to compute an available path per traffic request.
- Spectrum-Constraint Path Vector Searching (SCPVS), which partitions the nodes into different levels and uses a greedy approach to add leaves for each level until a path containing optimum cost is found.

However, the proposed algorithms are quite general and do not specify how to represent the subcarriers and allocate them after finding a path as done in our paper. In addition, our paper takes multiple modulation formats and regenerator nodes into account. Most of the related work focuses on optimal design of OFDM-based networks, under the condition that the traffic is known in advance. Our work assumes that the traffic is arriving in an on-line fashion, and the aim is to achieve a low blocking probability.

VI. Conclusions

We have proposed a load-aware and impairment-aware algorithm for SLICE optical networks. Our algorithm is designed to operate with dynamic traffic. By allocating weights to represent the utilization of each fiber link, it tries to accommodate the traffic in a balanced manner. The proposed algorithm efficiently makes use of the regenerator nodes and only restores the signal when necessary. A suitable modulation format that consumes the fewest subcarriers is selected for each traffic request. The simulation results indicate that the proposed algorithm outperforms, with respect to blocking probability, a load-unaware routing algorithm and algorithms using a fixed modulation format. In comparison to weight functions of existing dynamic routing algorithms, the results are also encouraging, since our algorithm seems to strike the right balance between load balancing and path length, which on its turn pays off through a low blocking probability.

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