Connection Provisioning in Spectrally-Spatially Flexible Optical Networks with Physical Layer Considerations

G. Savva[1], K. Manousakis[1], B. Shariati[2], I. Tomkos[3], and G. Ellinas[1]

[1]*KIOS CoE and Department of Electrical and Computer Eng., University of Cyprus, 1678 Nicosia, Cyprus*

[2]*Universitat Politécnica de Catalunya (UPC), 08034 Barcelona, Spain*

[3]*Athens Information Technology, Marousi, 15125 Athens, Greece*

e-mail: savva.giannis@ucy.ac.cy

ABSTRACT

This paper presents efficient connection provisioning techniques for spectrally-spatially flexible optical networks (SS-FON) utilizing multicore fibers (MCFs) when physical layer effects are taken into consideration. To account for the physical layer effects, two approaches are presented that are used to establish a given set of demands. One approach is to provision the requests that have acceptable quality-of-transmission (QoT) assuming a fully-loaded network for specific modulation formats, so that in the future these connections will remain feasible when subsequently new connections are established. This approach restricts the candidate path space to ensure that an established connection has acceptable QoT irrespective of the network state. The second approach is to take into account the current state of the network during the provisioning of each connection request. In the latter approach, the algorithm has to also ascertain if the establishment of a new connection will negatively impact some of the already established connections. Network resource utilization and connection blocking metrics are considered during the design of the provisioning techniques while also accounting for the PLIs.

Keywords: routing spectrum and core allocation, spatial division multiplexing, physical layer impairments.

1. INTRODUCTION

In spectrally-spatially flexible optical networks (SS-FONs), when considering connection provisioning, the routing, spectrum and core allocation (RSCA) problem must be solved, that includes finding a path (Routing), the required spectrum, and the core in the path that can be allocated (SCA) for the given demands [1]. In the RSCA problem, a feasible solution must satisfy several constraints: (i) the *spectrum continuity* constraint, where a demand must be allocated on the same frequency slots across all the links of the selected path, (ii) the *non-overlapping* constraint, which ensures that a frequency slot is allocated to one demand at a time, and (iii) the *spectrum contiguity* constraint, which implies that the number of frequency slots used to serve a demand have to be contiguous. Further, core allocation is constrained by the switching capabilities of the optical nodes; in independent switching (*Ind-Sw*), switching between any pair of cores is allowed, while in joint switching (*J-Sw*) only switching to the same core is allowed. Hybrid approaches can also be used that relax the same core constraint, where a group of cores can be directed to another specific group of cores [2].

Moreover, physical-layer impairments (PLIs) must be taken into account when establishing connections in SS-FONs, as they can potentially have detrimental impact on a number of the connections established in the network. Due to PLIs, routing choices made for one connection affect and are affected by the routing choices of other connections. Hence, a connection in the network may be blocked due to (i) the non-availability of free spectrum slots due to the spectrum utilization of existing connections (network-layer blocking) and (ii) the physical layer impairments, introduced by the non-ideal physical layer, which may degrade the signal quality to the extent that the lightpath is not feasible (does not meet the QoT specifications - physical-layer blocking). Therefore, a solution to the RSCA problem must consider both blocking categories.

This work focuses on MCFs and presents heuristics to solve the RSCA problem in SS-FONs while also taking into account QoT constraints. A static provisioning problem is considered, and the objective is to reduce the blocking probability of the network, while also accounting for the PLIs. Two different approaches are initially presented relating to the state of the network in order to quantify the path search space for the routing process. Subsequently, several PLI-RSCA algorithms based on these two approaches are presented.

2. PHYSICAL LAYER IMPAIRMENTS AND QoT IN SS-FONs

In order to account for the PLIs, the QoT estimator tool presented in [4] is used. This tool calculates the QoT of new lightpaths to be established in the network as well as the impact on existing connections when setting up a new one, by taking into account the analytical models of linear and nonlinear impairments of SS-FONs. The tool input comprises of the network topology, spectral windows, link characteristics, signal types (baud rate and modulation format), as well as lightpaths currently established in the network. The impact of the PLIs on each established connection depends on the links of the path, the optical fiber's physical characteristics (e.g., number of adjacent cores and the distance between them), the number of allocated frequency slots operating at the same frequency in the adjacent cores, as well as the modulation format used at each frequency slot.

An approach to address the PLI-RSCA problem would be to calculate the QoT for each of the candidate paths under the assumption that the network is fully loaded and, if acceptable, include it in the path space. Then, any connection using this path will have an acceptable QoT regardless of the network's future state. However, such an approach reduces the candidate path space. On the other hand, algorithms that take into account the current utilization state of the network to account for the interference among lightpaths explore a larger path space (note that, the larger the number of candidate paths, the larger the search space for each requested connection, and the higher the possibility of finding available resources). The drawback of this second approach is that the problem becomes more complex, since the algorithm now has to consider the utilization state of the network for each connection provisioned, so that the chosen lightpath has acceptable QoT and also does not impact negatively any of the already established connections (making them infeasible). A related analysis has been performed for WDM networks in [3]. Also, note that, since all the techniques proposed in this work (described in Section 3) use a pre-processing step to obtain, sort, and evaluate the QoT of the all candidate paths, compared to existing algorithms that calculate the spectrum needed using each path to serve a demand and then sort the demands, these proposed techniques will also present an advantage in terms of computational complexity.

Thus, in this work, in order to account for the PLIs during the RSCA, two different types (*Type 1* and *Type 2*) of candidate path spaces are considered. Paths within the *Type 1* candidate path space are the ones that meet the QoT constraint (evaluated using the QoT estimator tool) with the assumption that the network is empty. In this case, with the network empty, the only PLIs considered are the ones that affect the lightpath itself (e.g., attenuation, dispersion, etc.). The *Type 2* candidate path space includes paths that meet the QoT constraint when the network is fully loaded (all spectrum slots on all links on the path are utilized). To define the *Type 2* candidate path space, a simulation-based procedure is utilized for different demands; paths that have acceptable QoT are included in the candidate path space, while the rest are discarded, ensuring that the chosen candidate paths are feasible, irrespectively of the network state. In this case, with the network fully loaded, the PLIs considered are both the ones that affect the lightpath itself and the ones due to the interactions of the lightpath under investigation with other lightpaths currently established in the network.

To illustrate this, an example is used to quantify the degree to which the routing solution space is reduced when PLIs are considered. Since the chosen modulation format affects significantly the PLIs, this space is also quantified for different modulation formats. The Telefonica network (Fig. 1(b)) is considered, with the assumption that there is a single connection request for all source-destination pairs in the network. For this set of connection requests, *k*-shortest paths are initially calculated, for different values of the parameter *k*, and this set of candidate paths is subsequently pruned using the QoT estimator tool. Table 1 shows that, as expected, the number of paths obtained after eliminating candidate paths due to the impairments of *Type* 1 (column (b)) is larger than when the fully-loaded network assumption was used for the impairments of *Type* 2 (column (c)).

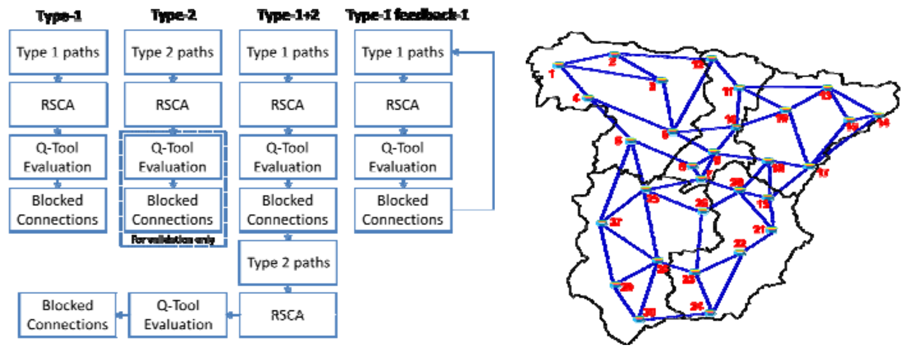
Table 1. Candidate path space for different types of PLIs and modulation formats (Telefonica network).

k	(a) Set of *k* candidate paths	(b) Set of *Type* 1 paths			(c) Set of *Type* 2 paths		
		QPSK	8-QAM	16-QAM	QPSK	8-QAM	16-QAM
1	870	870	870	822	828	826	762
2	1740	1740	1740	1622	1660	1660	1506
3	2610	2610	2610	2398	2504	2504	2216
4	3480	3480	3480	3146	3338	3338	2902
5	4350	4350	4350	3866	4184	4180	3860

A PLI-RSCA algorithm with the fully-loaded network assumption, that explores the solution space that corresponds to column (c), is expected to obtain zero physical-layer blocking. Thus, connections will only be rejected due to lack of available frequency slots (network-layer blocking). Moreover, the selected lightpaths are not expected to become infeasible by the establishment of future connections. However, such an algorithm explores a smaller solution space that restricts unnecessarily the RSCA choices, compared to an algorithm that takes into account the utilization state of the network and explores the solution space that corresponds to column (b). This may lead to deterioration in the performance of the RSCA algorithm that assumes a fully-loaded network condition (i.e., higher network-layer blocking). Performance evaluation results in Section 4 investigate these trade-offs for various proposed RSCA algorithms as described below in Section 3.

3. RSCA ALGORITHMS WITH PHYSICAL LAYER IMPAIRMENTS CONSIDERATION

This section presents a series of RSCA algorithms that take into account these two different sets of candidate paths. The focus is on MCFs for a network planning scenario and heuristic algorithms are presented to solve the RSCA problem while also taking into account QoT constraints. In order to solve the Routing problem, a *k*-shortest path algorithm is developed that finds the "best" *k* paths that can satisfy a given demand. The criterion that is chosen in order to sort the candidate paths for every modulation format is the overall physical distance of the path and the number of hops in the path (hybrid metric as described in [5]). To establish a connection, the algorithms choose the first path from the sorted list with the highest score in the hybrid metric. For the spectrum and core allocation (SCA) problem, the algorithm chooses the first available continuous and contiguous slots across the links of the path starting from the first core. In the case where there are no available slots for that path, other paths from the list are checked. Core switching constraints are also imposed, when performing the core allocation for each connection. If no path is found that can serve the given connection, then the connection is rejected. In Fig. 1(a), four different algorithms are proposed. Each algorithm differs in the type of paths it takes as input and the number of steps it uses to establish a given set of demands.



(a) (b)

Figure 1. (a) Flowcharts of the proposed algorithms, (b) Topology of the Telefonica network [2].

Type-1 algorithm: Uses as input the *Type 1* path space. The algorithm performs spectrum and core allocation based on the first-fit policy for each given connection. Finally, the established lightpaths are evaluated through the QoT estimator tool and the paths that do not have acceptable QoT are rejected. Since this is a PLI-unaware RSCA approach, the QoT estimator tool will reject a significant percentage of demands.

Type-2 algorithm: Uses as input the *Type 2* path space. Each connection is again served based on the first-fit policy. Since this algorithm uses paths from the *Type 2* path space, any connection established in the network will have acceptable QoT irrespective of the network state. Thus, the QoT evaluation step is added as a validation step. Using this approach, connections will be rejected only due to unavailability of network resources for this smaller set of available paths.

Type-1+2 algorithm: Based on both *Type 1* and *Type 2* path spaces. As shown in Fig. 1(a), demands are first established using the *Type 1* path space. Then, connections are evaluated by the QoT tool and the ones that are blocked are served (if there are available network resources) using paths from the *Type 2* path space. As a result, connections that were previously blocked due to PLIs will now have an acceptable QoT. However, previously allocated connections may also be affected. In this case, new connections will be established and affected ones will be rejected only if the overall resulting blocking probability is reduced.

Type-1 feedback-1 algorithm: Based on a *customized Type 1* path space for the given state of the network using a feedback-based procedure that aims to minimize the number of connections that cannot be established in the network due to QoT considerations. First, demands are served using the *Type 1* path space and all established connections are evaluated using the QoT tool. Then, for each blocked connection, the path and the modulation format used are excluded from the *customized Type 1* path space, since this path is not feasible for the given network state. These (blocked) demands are re-routed in the network and this procedure is repeated until all rejected connections are now feasible or the number of feedback loops reaches a predetermined threshold (n).

4. PERFORMANCE EVALUATION

The simulation setup used to evaluate the proposed algorithm is as follows: the SS-FON is implemented using bandwidth variable transponders (BV-Ts) that operate using multiple modulation formats: QPSK, 8-QAM, and 16-QAM. The transmission reach for each modulation format is given by 4600, 1700, and 800 km respectively. Moreover, a flexible grid is implemented with channel spacing of 25 GHz and baud rate of 16 GBaud. For the performance evaluation, the Telefonica network which consists of 30 nodes and 56 undirected links was used (Fig. 1(b)). In all cases, demands are randomly generated using a uniform distribution (all source-destination pairs are equally likely and each demand size varies from 40 to 200 Gbps). Each experiment is performed for 5 sets of demands and the average of these results is presented, while the assumption is that for each source-destination pair the algorithm pre-calculates a set of 5 shortest paths (i.e., k=5). In Fig. 2, the blocking probability (Fig. 2(a)) and the number of demands utilized for each algorithm (Fig. 2(b)) are presented.

In all evaluation steps, a BER of 10^{-3} was used as a threshold value [4]. Hence, any connection with a higher BER is classified as rejected by the QoT estimator tool. Also, for all scenarios it is assumed that the core allocated for a given demand is the same through all links in the path. As shown in Fig. 2(a), the *Type-2* algorithm has higher blocking probability than any other approach. All connections established are feasible (considering PLIs), but due to the smaller space of the candidate paths used to serve each connection, demands are blocked due to the lack of network resources. On the other hand, the feedback-based approach outperforms all approaches, since it provides the lowest blocking probability for the given connections. This is due to the use of the *Type 1* path space that has as a result the minimization of network blocking and the use of the QoT estimator tool to create a (customized) path space that aims to minimize the blocking due to PLIs. Also, *Type-1* and *Type-1+2* algorithms lie between the other two algorithms, while *Type-1+2* performs better than the *Type 1* approach due to the additional step that examines *Type 2* paths for the previously blocked connections. Moreover, the blocking probability of all the algorithms increases significantly after 4000 connection requests, since now the limitation is the number available resources rather than the algorithms used. Finally, the blocking probability of the *Type-1 feedback-1* depends on the chosen feedback loop threshold; for example, for thresholds n=1-5, the blocking probability is equal to 0.028, 0.0258, 0.0246, 0.0244, and 0.0244, respectively, for 5000 connections. Thus, as expected, blocking probability decreases with increasing thresholds, but at the same time the computational complexity increases as well.

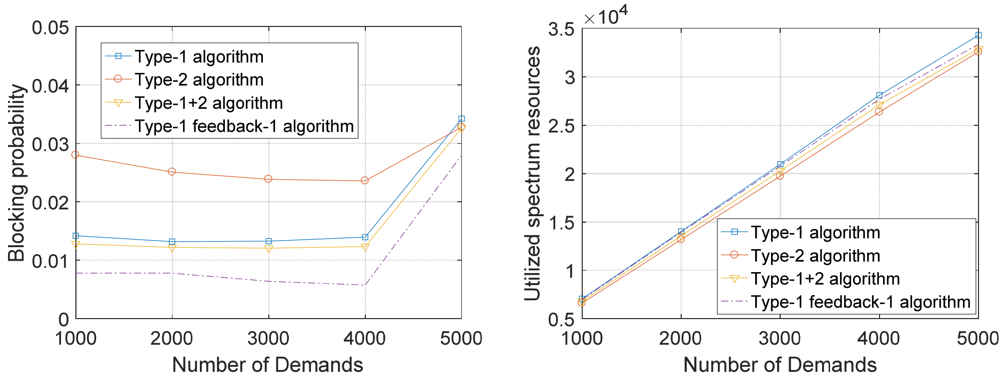


Figure 2. (a) Blocking probability and (b) utilized spectrum resources for the 4 different proposed approaches.

All algorithms use a similar number of spectrum resources to accommodate the connections (Fig. 2(b)). It is noted that, while the feedback-based approach uses the same amount of resources, it can establish more connections as shown in Fig. 2(a). This is due to the larger initial path space used (*Type 1*) and the customization of the path space due to the feedback approach. It is also worth noting that the mean number of slots per established connection is equal to 7.09, 6.75, 6.862, and 7.07 for *Type-1*, *Type-2*, *Type-1+2*, *Type-1 feedback-1*, respectively, and depends on the number of hops and the modulation format that every algorithm chooses.

5. CONCLUSIONS

This work presents a series of RSCA algorithms that also account for the PLIs. Utilizing a hybrid (distance and number of hops) routing criterion, two different approaches are followed to create different sets of candidate paths used as input to the RSCA algorithms. In the first set, the paths have acceptable QoT under the assumption that the network is empty; in the second, the paths have acceptable QoT under the assumption that the network is fully loaded. Subsequently, different RSCA techniques are proposed and evaluated, aiming to minimize connection blocking. Performance results quantify the improvements that can be obtained using the feedback-based PLI-aware RSCA algorithm that takes into account the network state to create a "customized" path space, as opposed to algorithms that do not consider impairments or consider impairments assuming a fully-loaded network interference scenario. Specifically, using the aforementioned algorithm, the blocking probability of the network is decreased, while the utilization of spectrum resources remains similar to the rest of the techniques.

ACKNOWLEDGEMENTS

This work has been supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 739551 (KIOS CoE) and from the Government of the Republic of Cyprus through the Directorate General for European Programmes, Coordination and Development. This work has also received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA Grant Agreement No 630853.

REFERENCES

[1] M. Klinkowski et al., "Survey of Resource Allocation Schemes and Algorithms in Spectrally-spatially Flexible Optical Networking," *Optical Switching and Networking*, 27:58-78, Jan 2018.

[2] B. Shariati et al, "Impact of Spatial and Spectral Granularity on the Performance of SDM Networks based on Spatial Superchannel Switching," *IEEE/OSA J. Lightwave Technol*., 35(1):2559-2568, 2017.

[3] K. Christodoulopoulos et al., "Considering Physical Layer Impairments in Offline RWA", *IEEE Network*, 23(3): 26-33, 2009.

[4] B. Shariati et al., "Spectrally-Spatially Flexible Optical Networking", *Proc. ACP*, 2016.

[5] G. Savva et al., "Physical Layer-Aware Routing, Spectrum, and Core Allocation in Spectrally-Spatially Flexible Optical Networks with Multicore Fibers", *Proc. ICC*, Kansas City, MO, May 2018.