Joint Core and Spectrum Allocation in Dynamic Optical Networks with ROADMs with No Line Changes

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Abstract. Future metro networks will connect many multiaccess edge computing resources (MEC) working in a coordinating fashion to provide users with cloud computing capabilities with very low latency. That highly distributed computing architecture has to be connected by a network that provides high bandwidth and flexibility. Elastic optical networks (EONs) are currently the best option to perform that task. In a next step of optical network evolution, EONs can increase the bandwidth that they provide by using multicore fibers (MCF). When dynamic optical circuits are established in these networks, the routing, core and spectrum assignment (RCSA) problem must be solved. In this paper, two algorithms are presented in order to solve the RCSA problem considering continuity constraints in both the spectrum and the core (as we consider a cost-effective metro network architecture based on ROADMs without line changes). One of these versions explores the full spectrum of all cores in order to grant the best solution when solving the RCSA problem. The results of a simulation study show that exploring all the cores when solving the RCSA problem can reduce the blocking ratio of those networks and, therefore, increase its performance at the expense of a slight increment of the computing time required to provide a solution.

Keywords: RCSA · Routing · Spectrum assignment · Core assignment · Multicore fibers · Elastic optical networks

1 Introduction

The explosion of paradigms like the Internet of Things (IoT), Tactile Internet or Industry 4.0 are inducing an evolution of communication infrastructures. The new application and services as well as the number of connected devices impose stringent requirements that current networks cannot satisfy [1]. 5G is a promising technology for that evolution, as it supports a high number of connected devices and enables high-capacity and low latency communications [2]. At the same time, the offshoring of computing and storage capacity from data centres (DCs) to the edge of the network thanks to Multi-access Edge

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H. Gao et al. (Eds.): BROADNETS 2020, LNICST 355, pp. 154–162, 2021.
https://doi.org/10.1007/978-3-030-68737-3_10

Computing (MEC) or fog computing technologies puts processes closer to the end-user helping to reduce the latency, one of the most stringent key performance parameters of 5G [3].

While the fronthaul of this architecture is based on wireless technologies, the backhaul will be based on fiber networks as they offer high bandwidth, dynamicity, scalability and reliability [4]. Current wavelength-routed optical networks (WRON) use wavelength division multiplexing (WDM) not only to increase the bandwidth but also for routing purposes when establishing lightpaths (i.e., optical circuits between network nodes not necessarily adjacent in the physical network) [5]. Lightpaths can be established and released on-demand improving the flexibility of WRONs. However, as current WRONs use ITU-T fixed channels to establish the lightpaths, they waste network capacity as they cannot accommodate traffic in the most effective way. In order to deal with such a problem, elastic optical network architectures were proposed. Elastic (or flexible) optical networks (EONs), thanks to the use of techniques like OFDM or Nyquist-WDM [6, 7], enable the allocation of a variable portion of spectrum to each optical connection according to its requirements. In these networks, when a lightpath request arrives (with information about the demanded bandwidth in addition to source and destination nodes), the control plane must determine the sequence of fibers (route) and a portion of spectrum in order to establish the lightpath. This problem is known as the routing and spectrum allocation (RSA) problem [8] and can be solved by a central entity (e.g., path computation element, PCE).

The next step in the evolution of EONs is the use of multicore fibers (MCFs), which expand the network capacity by using space division multiplexing, at the expense of increasing the crosstalk between cores. When EONs are equipped with these fibers, the RSA problem is transformed into the Routing, Core and Spectrum Assignment (RCSA) problem adding a new degree of complexity to the RSA problem [9]. In the literature, there are some proposals to solve the RCSA problem [9–14]. In most of them, even when they consider the spectrum continuity constraint (i.e., there are not wavelength converters in the network and the lightpath must use the same spectrum in the complete route), they do not consider core continuity constraints when solving the RCSA problem. However, in [14], it is shown that using an architecture based on ROADMs without line changes (therefore, imposing the core continuity constraint) is much more economic at the expense of a little performance reduction.

In this paper, we propose two methods to solve the RCSA problem in a dynamic network scenario in which lightpaths are established and released on real time. In this kind of scenarios, the main goal is to establish all the connections requested by end users, but, as that is not always possible due to limited network resources, the objective is to reduce the ratio of non-established (or blocked) lightpath requests. We have considered that all lightpath establishment requests are solved by a PCE and assumed a metro network architecture connecting MEC resources using ROADMs without line changes [14]. Hence, our proposals consider continuity constraints in both the spectrum and the core assigned to the lightpath. In contrast to the RCSA method used in [14], which is based on first-fit when solving the spectrum assignment, in our work, the spectrum slot that better fits the connection request capacity is selected. Moreover, we show that solving the core and spectrum assignment jointly, improves the performance, as it minimizes the blocking probability of the requests.

2 Algorithms for Solving the Dynamic RCSA Problem

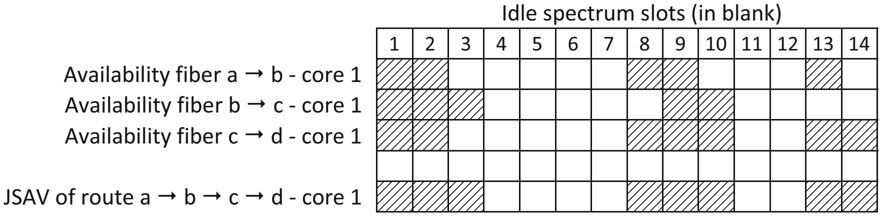
Solving the RCSA problem in dynamic networks with centralized control is the extension of the RSA problem in elastic networks when they operate in networks equipped with MCFs. Users demand the establishment and release of lightpaths on real time. In their requests, users indicate the source and destination node of the lightpath as well as the required bandwidth of the optical circuit. In centralized architectures, a central element, like a PCE, has to assign resources to establish the lightpath, i.e., find a route, a core in each fiber of the route and a portion of the spectrum. If there are enough idle resources, the lightpath is established, and it is rejected otherwise [7]. The connection will not be permanently established but it will be torn down at some point in the future, i.e., lightpaths have a limited duration.

Most of works in flexible networks consider that the spectrum is divided into frequency slots, i.e., narrow spectrum segments of a given width in GHz, all of them with the same bandwidth. When a lightpath request arrives at the PCE, the RCSA algorithm will assign as many available slots as needed to allocate all the bandwidth required by the user in a superchannel. If no waveband conversion is used, the same portion of spectrum must be reserved in all the fibers of the route. It is important to note that a guard-band is reserved between two consecutive demands in the spectrum to avoid interference between them. One of the metrics to evaluate the performance of the method that solve the dynamic RCSA problems (assuming that all requests demand the same capacity) is the blocking ratio, i.e., the portion of the connections which cannot be established due to lack of resources.

Some works from literature solve the problem of determining the modulation level of the lightpath when solving the RCSA problem, resulting in the RMCSA (Routing, Modulation, Core and Spectrum Assignment) problem. Determining the modulation level is clearly affected by physical impairments. Some papers deal with that problem, adding a constraint in the modulation level used by the lightpath depending on its length. Other studies also take into account the crosstalk between signals traveling in different cores when solving the RCSA problem in networks equipped with MCFs [9–13]. When the inter-core distance is high enough, the crosstalk is negligible [9]. Inter-core crosstalk is also influenced by the length of fiber link (the higher link length, the higher the impairment caused).

In this study, we have focused on solving the RCSA in future metro networks (backhaul of 5G networks equipped with MEC resources) where the distance will be short enough to use the best modulation available (i.e., with the highest spectral efficiency) and the influence of inter-core crosstalk is also limited. Moreover, it is also expected that the number of cores in a MCF installed in a metro network will not be very high and, therefore, the inter-core distance will be high enough to avoid considering the physical impairments in such a scenario. Furthermore, we envision a metro network architecture equipped with ROADM without line changes [14]. In such architecture, the RCSA problem has to be solved considering both core continuity and spectrum continuity constraints.

In our proposal, routing is solved using pre-calculated *k*-shortest paths in a graph where each network node is represented as a vertex and each MCF as an edge. Then, each time that a lightpath request arrives at the PCE, it will use the information from the TED (Traffic Engineering Database) to build the joint spectrum availability vector (JSAV) of each of the fiber cores of each route. Figure 1 shows the construction of the JSAV of the route a → b → c → d using core 1. Let us assume that only that path (and that core) is considered as a candidate for establishing the connection in this example. As it can be seen in that figure, there are two idle spectrum slices to establish new lightpaths: from slot 4 to 7 (4 slots) and from slot 11 to 12 (2 slots). If a connection request arrives at the network and requires two spectral slots (including guard-bands), it can be placed in both gaps. However, if a first-fit strategy for spectrum assignment is used, that is, if the first available gap is selected for allocating this request (for instance, using slots 4 and 5), the resulting spectrum will then have two gaps of two slots. Therefore, if a new lightpath request arrives in that moment demanding three or four slots, it will be blocked (since there are no available gaps of that size, and no more candidate paths in this example). In contrast, if slots 11 and 12 had been selected to allocate the first request, the new request would have also been successfully allocated. Our RCSA methods follow this idea and they look for the gap that better fits the request (a gap with equal size to the request, or the smaller between those with more slots than required). Therefore, instead of employing a first-fit strategy for spectrum assignment as in [14], a best gap strategy is used.



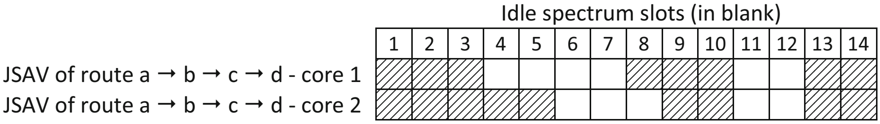
Idle spectrum slots (in blank)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Availability fiber a → b - core 1	▨	▨						▨	▨				▨	
Availability fiber b → c - core 1	▨	▨	▨						▨	▨				
Availability fiber c → d - core 1	▨	▨						▨	▨	▨			▨	▨
JSAV of route a → b → c → d - core 1	▨	▨	▨					▨	▨	▨			▨	▨

Fig. 1. Construction of the JSAV of route a → b → c → d in core 1.

Regarding the selection of the cores, some studies use the first-fit technique [11, 14], i.e., the first core with spectrum availability is selected. Other studies also follow first-fit method, but take into account the inter-core crosstalk [10, 12, 13]. However, apart from [14], all of them consider an architecture with line changes and, therefore, they do not impose the core continuity constraint.

However, the use of MCF can be better exploited if the selection of the core and the assignment of spectrum is done jointly, with the aim of finding the best gap by considering the spectrum availability of all the cores. Figure 2 shows an example of these two strategies: (i) using first-fit for core assignment and best gap for spectrum allocation, and (ii) searching for the best gap along all cores for a joint allocation of core and spectrum. Suppose that a user requires the establishment of a lightpath demanding three spectral slots (including guard-bands). Figure 2 shows the JSAVs of route a → b → c → d using core 1 and core 2. If first-fit is used for core assignment, the method will assign the gap 4 to 6 in core 1 for that connection, thus leaving an isolated idle slot in slot 7. However, the second method, finds the gap that better fits the request along all the cores, which is placed in slots 6–8 in core 2.



	Idle spectrum slots (in blank)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
JSAV of route a → b → c → d - core 1	▨	▨	▨					▨	▨	▨			▨	▨
JSAV of route a → b → c → d - core 2	▨	▨	▨	▨	▨				▨	▨			▨	▨

Fig. 2. Example JSAV of route a → b → c → d in core 1 and core 2.

In summary, in [14], a first-fit method is used for core selection, and also for spectrum allocation. In contrast, in this paper we propose and analyze two methods. The first one uses a first-fit approach for selecting the core, and a best gap method for spectrum allocation (Algorithm 1 and first-fit core assignment in the figures). The second method looks for the best gap along all the cores, thus solves the core and spectrum allocation subproblems jointly (Algorithm 2 and best core assignment in figures).

```
Algorithm 1: first-fit core assignment Heuristic
 1: Procedure first-fit_core_assignment(network_state, source_node, destination_node,
    bandwidth_required)
 2:   bandwidth_required ← bandwidth_required + guard_bands
 3:   number_slots_required ← determine_number_slots_required(source_node,
                                  destination_node, bandwidth_required)
 4:   transmitters_assigned_to_lightpath ← assign_transmitters(source_node,
                                  number_slots_required)
 5:   receivers_assigned_to_lightpath ← assign_receivers(destination_node,
                                  number_slots_required)
 6:   if transmitters_assigned_to_lightpath ≠ ∅ and
        receivers_assigned_to_lightpath ≠ ∅ then
 7:     for each path in k-shortest-paths(source_node, destination_node) do
 8:       for each core in cores_per_MCF do
 9:         JSAV ← build_JSAV(path, core)
10:         slots_assigned_to_lightpath ← best_gap_spectrum_allocation(path,
                                  JSAV, number_slots_required)
11:         if slots_assigned_to_lightpath = ∅ then
12:           continue   # Not enough contiguous slots found on JSAV (jump to line 8)
13:         end if
14:         establish_lightpath(path, core, slots_assigned_to_lightpath,
                transmitters_assigned_to_lightpath, receivers_assigned_to_lightpath)
15:         go to end procedure
16:       end for
17:     end for
18:   end if
19:   reject_lightpath()
20: end procedure
```

Algorithm 2: best-fit core assignment Heuristic

```
 1: Procedure best_core_assignment(network_state, source_node, destination_node,
                                   bandwidth_required)
 2:   bandwidth_required ← bandwidth_required + guard_bands
 3:   number_slots_required ← determine_number_slots_required(source_node,
                                   destination_node, bandwidth_required)
 4:   transmitters_assigned_to_lightpath ← assign_transmitters(source_node,
                                   number_slots_required)
 5:   receivers_assigned_to_lightpath ← assign_receivers(destination_node,
                                   number_slots_required)
 6:   if transmitters_assigned_to_lightpath ≠ ∅ and
        receivers_assigned_to_lightpath ≠ ∅ then
 7:     for each path in k-shortest-paths(source_node, destination_node) do
 8:       combined_JSAV ← ∅
 9:       for each core in cores_per_MCF do
10:         combined_JSAV ← combined_JSAV ∪ build_JSAV(path, core)
11:       end for
12:       core_and_slots_assigned_to_lightpath ← best_gap_spectrum_alloca-
                tion(path, combined_JSAV, number_slots_required)
13:       if core_and_slots_assigned_to_lightpath = ∅ then
14:         continue  # Not enough contiguous slots found on JSAV (jump to line 7)
15:       end if
16:       establish_lightpath(path, core_and_slots_assigned_to_lightpath,
                transmitters_assigned_to_lightpath, receivers_assigned_to_lightpath)
17:       go to end procedure
18:     end for
19:   end if
20:   reject_lightpath()
21: end procedure
```

3 Simulation Study

3.1 Simulation Scenario

In order to evaluate the performance of the algorithms, we have implemented a simulator of EONs using OMNeT++ [13]. As we want to test our proposal in a mesh metro network, the physical network topology used for this study is the 14-node NSFNet (a very well-known mesh topology but adapting its distances to the range of metro networks). Each cable between two network nodes is assumed to consist of two MCFs (one for each direction). Each MCF has two cores. The available capacity in each core is 4 THz and no physical impairments are considered. Four different slot sizes have been considered: 12.5 GHz (like most EONs proposals) and 50 GHz (the classical slot size uses in WRONs). The guard-band width is 10 GHz.

Lightpath requests arrive at the network following a Poisson process and the source-destination nodes pairs of each request are randomly selected using a uniform distribution. The demanded bandwidth of each lightpath is selected randomly following a uniform distribution between 1 GHz and 300 GHz, and the holding time of a connection is obtained by means of an exponential distribution. The number of paths explored with the *k*-shortest paths method was set to 2 routes per node pair. All the results are shown with 95% confidence intervals (although in most cases they are smaller than the size of the symbols employed in the following figures).

3.2 Simulation Results

Figure 3 shows the blocking ratio of lightpaths depending on the load, the size of the slots and the method followed to assign the core: first-fit or best core. Results from Fig. 3 shows that the blocking ratio of the network increases with the load. Moreover, independently of the method followed to assign the core, using a smaller slot size improves the network utilization and increases its performance by reducing the blocking ratio. Finally, Fig. 3 also shows that thank to the joint allocation of spectrum and core (best core assignment), the blocking ratio of the network is reduced when compared to the method that uses first-fit for core assignment.

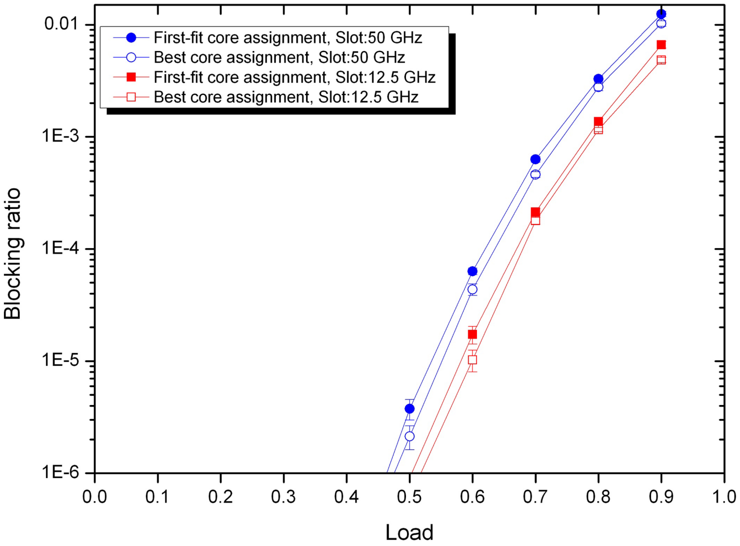


Fig. 3. Blocking probability of connection request depending on the load when using (i) first-fit for core assignment and best gap for spectrum assignment, and (ii) joint core and spectrum allocation (best core), with two slot sizes: 12.5 GHz and 50 GHz.

One of the main concerns of exploring the full spectrum of all the cores (required for the joint core and spectrum allocation) is the computing time required to obtain a solution. In dynamic networks, this time is critical as connections should be served on real time. Even when the best core method can be easily parallelized, thus reducing its computing time, for the sake of comparison, no parallelization has been used in our tests. Figure 4 shows the computing time with the different versions of the RCSA algorithm.

Figure 4 shows that when the slot size decreases, the computing time required to solve the RCSA problem increases, as there is a higher number of slots that must be explored to provide the solution. When comparing the computing time of the two versions of the RCSA algorithm, the first-fit version is the one that has a lower computing time, as it sequentially explores the spectrum of the cores, but when a solution is found in one core, no other cores are evaluated. On the contrary, the joint allocation of core and spectrum explores the spectrum of all the cores to find the best gap along all the cores. However, the computing time of both versions is very similar for low and middle loads where, according to Fig. 3, the blocking ratio is below 10^{-3}. In any case, the computing time of all the tests are under 30, ms and that is a low value compared with the time required to physically establish (configuring the involved resources) and to activate the lightpaths.

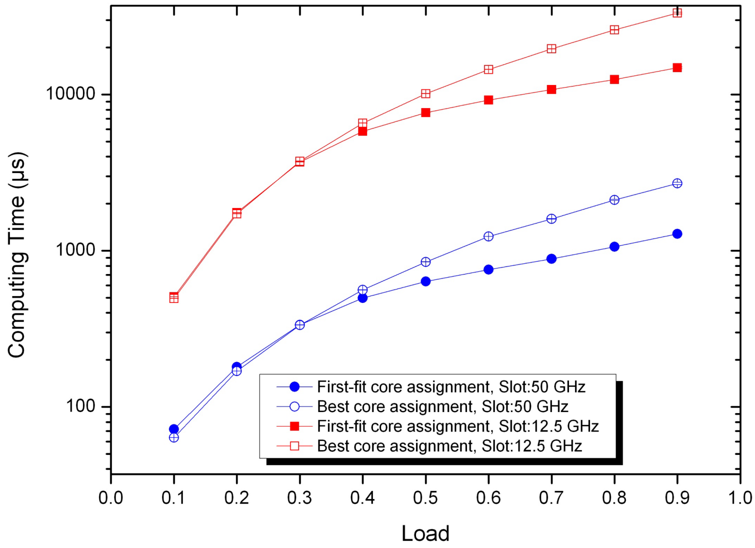


Fig. 4. Computing time that (i) first-fit for core assignment and best gap for spectrum assignment, and (ii) joint core and spectrum allocation (best core), take to solve a connection request depending on the load and using with two slot sizes: 12.5 GHz and 50 GHz.

4 Conclusions

In this paper, we have presented two algorithms for solving the routing, core and spectrum assignment for a metro elastic optical network equipped with multicore fiber and ROADM without line change. That cost-effective architecture provides the bandwidth and flexibility required for the backhaul of 5G networks equipped with MEC resources. Lightpath requests and releases are assumed to arrive at the network on-real time and a PCE is in charge of searching the solution of the RCSA problem using the information in the TED. Both versions use k-shortest paths for solving the routing problem and find the spectrum gap that better fits the lightpath request. However, they differ in the way in which cores are assigned. First-fit sequentially explores each core and it stops when finding a possible solution while the joint allocation explores the spectrum of all the cores to find the best available gap. Simulation results show that the blocking ratio is reduced when using the joint allocation at the expense of slightly increasing the computing time required to find a solution. In any case, the computing time of both versions is low enough to use them in the described architecture. This work establishes the first step for more complex studies in which networks with higher number of cores will also be explored.

Acknowledgment. The research leading to these results has been supported in part by Spanish Ministry of Economy and Competitiveness through the project ONOFRE-2 (TEC2017–84423-C3–1-P) and the research network Go2Edge (RED2018–102585-T) and the European Regional Development Fund (ERDF) through the project DISRUPTIVE of the cooperation programme Interreg V-A Spain-Portugal (POCTEP) 2014–2020.

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