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Elastic optical bypasses for traffic bursts

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ABSTRACT

In this paper, we introduce elastic optical bypasses to offload traffic bursts in Elastic Optical Networks. Firstly, the principles of the proposed mechanisms are explained. Secondly, *the most spectral efficient path with the largest slices first* method is proposed as a bypass-path selection policy. Various proportions of resources reserved for optical bypasses and those available for the IP layer are considered in consecutive experiments. Simulation results indicate improvements in terms of bandwidth blocking probability, the average number of hops per accepted demand, and the overall spectrum occupation in comparison to the reference approach. All the proposed mechanisms are fully compatible with the Software-Defined Networking concept.

1. Introduction

Telecommunications networks are dimensioned to support traffic of various magnitude. The Internet traffic is often bursty, meaning that occasionally, large quantities of traffic arrive, and the network should be able to deal with that. The most common occurrence of traffic bursts is related to: traffic sent between data centers (e.g. regular backups), failures of network links or devices (rerouted traffic appears suddenly on new paths), emergency situations, important events and so on. The purpose of this paper is to provide an efficient solution to manage such traffic.

Data center networks handle traffic associated with various applications and each year the required bandwidth is increasing e.g. the amount of inter-data center (inter-DC) traffic will be multiplied by 4 during years 2015–2020 [1]. Traffic bursts may congest IP layers and increase the amount of rejected demands. Thus, to handle such a massive load, additional spectral resources are required in underlying transport optical networks. Commonly, optical resources are fully available in the IP layer for the purpose of lightpaths (LPs) establishment. Each LP is then abstracted in the IP layer as a virtual link. Contrary, bypass mechanisms assume that only a part of physical resources is available for the IP layer, whereas remaining resources are reserved for future bypass creation.

The concept of bypasses in the context of hidden optical resources activation is presented in [2,3], and [4]. The Automatic Hidden Bypasses (AHB) mechanism [2] first tries to accommodate demands at the IP layer. Only in case of congestion, the algorithm tries to set-up bypasses utilizing hidden optical resources. Bypassed traffic can be sent through a different path than the one established by the Open Shortest Path First (OSPF) protocol in the IP layer. Hence, the length of LP established for a bypass is equal or longer than the total length of virtual links omitted by this bypass. In [2,3], and [4] the Wavelength Division Multiplexing (WDM) technology for optical transport network layer is considered. However, WDM is expected to be replaced by the promising Elastic Optical Network (EON) technology that more efficiently utilizes spectral resources [5–7]. Therefore, in this paper we investigate automatic hidden bypass mechanisms in the IP-over-EON architecture.

In the EON layer, the available optical spectrum is divided into narrow frequency slots (frequency slices, FSs) of a given granularity (e.g. 6.25 GHz, 12.5 GHz, or 37.5 GHz) defined in [8]. The width of a FS corresponds to the bandwidth of an orthogonal frequency-division multiplexing (OFDM) subcarrier [9]. To provide an optical connection (a lightpath) between end nodes, optical resources (in terms of a number of adjacent slices) are allocated along links of an end-to-end path. Additionally, the appropriate modulation format is selected for optical transmission. The performance analysis of EON as well as some implementation aspects are summarized in e.g. [10,11]. The paper [10] presents different implementations of OFDM for optical transmission, whereas in [11] authors focus on aspects of physical layer, network planning, design and optimization.

In this paper, we propose bypass mechanisms aimed at reducing total bandwidth of all blocked demands in the IP-over-EON architecture. Bypasses are examined with different scenarios of hidden resources and under various traffic load conditions using a dynamic simulation model. The EON technology requires the Routing, Modulation Level (Format) and Spectrum Assignment (RMLSA) problem to be solved to set-up LPs between end nodes [12]. One of the RMLSA solutions widely discussed in the literature is a two-step method, where a path is determined

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firstly, and then the spectrum is allocated. For example, the shortest path first (SPF) algorithm selects a path based on the physical distance and optical resources are allocated along that path using the first fit policy. For the purpose of on-demand LPs setting for bypasses in IP-over-EON, we propose a novel *the most spectral efficient path with the largest slices first* (MSEwLSF) method. The aim of the MSEwLSF policy is to find a feasible lightpath along a path with the least utilized spectrum (not always the shortest one).

We evaluate the performance of path selection policies under different ratios of hidden resources and in comparison to non-bypass scenario. The proposed bypass mechanism is fully compatible with the Software-Defined Networking (SDN) concept regarding the network control architecture.

The remainder of this paper is organized as follows. Section 2 provides a description and references to the works related to bypasses provisioning using the SDN concept. Section 3 presents the basic concept of bypasses, as well as a novel bypass-path selection policy for IP-over-EON. In Section 4, simulation environment is described, while in Section 5 numerical results are shown and discussed. Finally, Section 6 concludes the work.

2. Related work

In this section, we describe related works on bypassing and classify them regarding the visibility of optical resources in the IP layer. We further divide group of works assuming visible resources into non-SDN solutions [13–18] and SDN-based concepts [19–24]. Specifically, resources of the EON layer are explored as optical resources. Finally, we describe solutions for SDN-based networks, where only some part of optical resources is visible for the IP layer. Particularly, we refer to our previous works [2,3,25].

2.1. Non-SDN solutions

Several works have already addressed the topic how to set bypasses assuming that all optical resources are visible in the IP layer. A survey [26] thoroughly summarizes those achievements. Therefore, only the most relevant works are briefly described. When traffic demands are known in advance then design algorithm framework such as iterative planning routing algorithm can establish bypasses [13,14]. To deploy the optimal virtual topology containing bypasses, decisions of reconfiguration are made based on observations performed during selected period of time. According to observed traffic changes, the capacity of virtual links (including bypasses) is increased or some existing links are deleted. However, IP traffic is directly allocated into the optical layer by configuring parameters such as the modulation format and the number of slices.

Another solution assuming that all of the optical resources are visible in IP has been introduced in [15]. Based on Ant Colony Optimization and using traffic grooming, the authors of [15] proposed a solution to find virtual topologies containing bypasses, e.g. routes in the virtual layer or lightpaths in the optical layer visible as virtual links. The bandwidth of requests is divided into a set of low-bandwidth flows focusing mostly on reusing existing lightpaths. In case when flow is blocked, one hop bypass is established and this bypass carries all traffic related to the request. The mechanism was evaluated in time-varying traffic network scenarios for two network topologies. Simulations assumed that optical layer was equipped with optical transponders specified for EON, however, only one modulation format was used for optical transmissions.

To serve dynamic demands, the authors of [16] proposed multilayer energy efficient algorithms. For a particular demand, new lightpath(s) can be set-up or, previously established lightpaths can be utilized. Proposed solution solves routing in the IP layer as well as the RMLSA problem in EON. The former maps demands onto LPs, the latter changes the configuration of transponders and allocates spectrum. The aim is to minimize energy consumption. Optical bypasses reduce processing in electric layer, and thus, lower overall power consumption.

Since EON can provide the huge bandwidth, it has been widely investigated in the context of DC traffic requirements (e.g.[17,18]). For example, to support inter-DC connections, hybrid transparent paths are introduced in [17]. Based on spectral efficiency and availability of transponders the proposed algorithm tries to find paths. It is assumed that some electrical nodes can be offloaded whereas a selected path combined one or few LPs. Another proposal [18] solves the problem of bandwidth allocation and virtual machine placement jointly. Utilizing optical switches LPs are established between electrical components. Then traffic can be routed through either an electrical or an optical path. As can be seen, presented solutions (including those for DCs) neglect the context of hidden resources.

2.2. SDN solutions

Finally, modular framework for dynamic multilayer allocation in the SDN-based network is proposed by the Application Centric IP/Optical Network Orchestration (ACINO) project [19,20] which assumes that requests are handled using multipath routing in IP layer based on the candidate paths. The set of routes contains both existing lightpaths and those that may be established. Additionally, an optimization of the IP layer based on traffic re-routing utilizing existing or potential lightpaths (including bypasses) has been introduced. Presented multilayer network architecture implements explicit (source-based) routing in the SDN-based network. Summarizing this part, it can be noticed that those works are focused on setting lightpaths and/or providing multipath routing in the IP layer. Moreover, the primary topology can be changed, whereas in our work it stays static.

Also some papers involve inter-DC traffic in SDN-based networks. For example, in [21] the SDN controller allocates and releases LPs to establish paths in IP. Setting LPs (including bypasses) minimizes costs and energy for virtual machine migrations. Furthermore, in [22,23] SDN controllers in IP and EON layers monitor the network status and the flow size. Based on these observations the proposed strategy decides which resources can be assigned for the new request. Additionally, to reroute a large flow from the IP layer to the EON layer a new LP is established. Nevertheless, the papers focus on restoration. In [24], the proposed algorithm estimates paths which satisfy the requested bandwidth and end-to-end latency for the inter-DC connectivity. Computed paths include existing virtual links (reusing spare available bandwidth of LPs) or new LPs. All established LPs derive virtual links in IP.

Only a few papers: [2,3,25] assume that optical resources are partially hidden for IP in the SDN-based network. Optical bypasses, called Automatic Hidden Bypasses (AHB) have been introduced in [2] for IP-over-WDM with the SDN controller, while reliability extensions to AHB have been presented in [3]. Furthermore, [25] presents bypasses for IP-over-EON. In these works, a multilayer network architecture employs hop-by-hop routing. Bypasses established on-demand are transparent to the IP layer which is not aware of their existence. As a result routing tables do not need to be updated after changes in optical layer. Analyzing the only proposition of bypasses for IP-over-EON presented in [25] it can be concluded that the model of the optical layer did not assume different modulation formats. Moreover inter-DC traffic has not been considered. Taking into account the growth of traffic related to data centers and to ensure comprehensive studies both different modulation formats and inter-DC bursts should be addressed during bypasses evaluation. Moreover, various path-based policies should be considered to allocate spectrum for bypasses.

As can be seen hidden resources remain unexplored and it is hardly possible to find works directly focused on the issues addressed in this paper. In this work, four modulation formats are considered for optical transmission, whereas bypasses are applied to adapt the network to inter-DC traffic fluctuations. Bypasses are established without interrupting active transmissions. Additionally, a novel bypass-based policy is proposed to allocate spectrum for bypass.

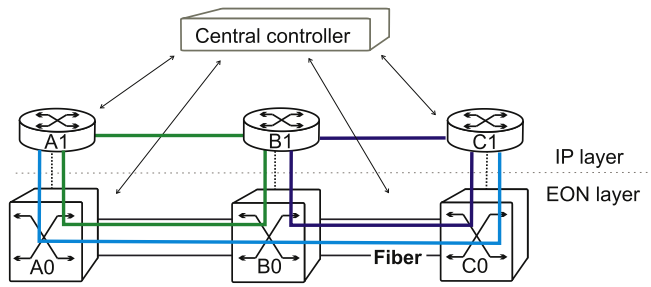


Fig. 1. An architecture example of IP-over-EON with bypasses.

3. Bypasses in IP-over-EON networks

This section describes the fundamentals of bypass-based routing mechanisms. Especially, the use of hidden resources is explained in the context of EON. Hidden resources are activated to set-up new LPs for requests blocked in the IP layer. Next, in order to achieve load balancing during bypass allocation, a novel bypass-path selection policy is introduced to determine paths in hidden spectrum and with only one hop in the IP layer.

3.1. Concept of elastic optical bypasses

We consider a simple multilayer network architecture comprising two layers: IP (virtual), where all high-capacity IP routers are located, and the optical (the EON layer) where optical nodes (cross-connects) are physically connected by optical links. We assume that, the flex-grid technology is employed in the EON layer. A router and an optical cross-connect connected together can be denoted as a node in a multilayer architecture. Thus, such a node comprises electronic and optical sections. Commonly, all of the optical resources are visible at IP and all resources are used for the purpose of creating virtual links. In this way all lightpaths are advertised as virtual links between routers in the IP layer. Routers are able to groom traffic in the electric layer. Moreover, full flexibility is assumed in a sense that each IP port is connected to a sliceable bandwidth variable transponder able to groom multiple traffic streams in the optical domain [27].

A significant difference introduced by bypass mechanisms is to reveal to the IP layer only selected optical resources. The remaining spectrum, denoted as hidden resources, can be used when congestions occur. Therefore, depending on allocated resources, an LP can be a virtual link or a bypass. When a request cannot be served in the IP layer due to the lack of resources, a new lightpath (bypass) is established, but a virtual link is not created. Fig. 1 shows an example of the IP-over-EON architecture with bypass established. As can be seen, virtual links are related to lightpaths visible in the IP layer, e.g. lightpath A0–B0 and B0–C0 handle virtual links between routers A1–B1 and B1–C1, respectively. In case of congestion in the IP layer on link A1–B1, a bypass A0–B0–C0 is established to offload the new traffic (incoming request), but new LP is not reported in IP layer. When transmission handled by the bypass ends, LP is torn down and resources are released.

The proposed concept can be easily implemented in SDN-based networks analogously to our previous works [2–4,25]. Specifically, the SDN controller collects information about traffic load, e.g. the amount of occupied bandwidth on the links. Simultaneously, the controller has full knowledge about the unoccupied hidden FSs as well as remaining link capacity in the IP layer. The algorithm of bypass mechanism starts on a new demand arrival and includes the following modules:

IP Module handles the demand using existing virtual resources if this is not possible, then

EON Module handles the demand using hidden resources dedicated for bypasses.

Algorithm 1 Bypass mechanism

```
Require: a new demand arrives
  Module IP (Identify the route in IP)
  if Route is not congested then
    Service in IP
  else
    Module EON (Try to establish the bypass)
    if hidden resources are sufficient then
      New lightpath is set
    else
      Demand is blocked
    end if
  end if
  Update network state
```

Pseudocode 1 describes the principle of the bypass mechanism.

In the IP Module the controller verifies if sufficient resources are available in the IP layer, and if so a traffic demand is served in that layer. The rationale is to maximize the utilization of resources available at the virtual layer (as well documented in [19]). If requested bandwidth cannot be guaranteed at IP, then the EON Module of the SDN controller is employed. In the EON Module hidden resources are expected to handle the new demand. What is important, the proposed RMLSA method is implemented in this module for the purpose of resource assignment. If setting of a bypass is possible, then hidden resources are allocated. When the EON Module also fails to handle the demand, the request is rejected. Any bypass established in the optical layer is composed of slices. The number of adjacent slices (N_{bypass}) required to handle bandwidth demand between two nodes (BW) along considered physical bypass-path p is calculated according to the following equation [28,29] and [30]:

$$N_{bypass} = \lceil \frac{BW}{M * \Delta_{slice}} \rceil + GB \tag{1}$$

where: $BW[Gb/s]$ denotes requested bandwidth; $M[b/s/Hz]$ is the spectral efficiency of the modulation format utilized on the bypass-path p; $\Delta_{slice}[GHz]$ denotes the width of frequency slice; GB is the number of slices for guard-band needed to separate adjacent optical transmission. To determine modulation format for a particular bypass, the SDN controller compares expected length of bypass-path and the maximum range of each modulation. The sum of link lengths included in the bypass-path cannot exceed the transmission reach of modulation selected for this path. Therefore, for a particular demand blocked in IP the width of the bypass depends on the requested bandwidth and modulation format used for transmissions between the IP nodes. In the reference case, in EON Module the SPF algorithm can be employed to find the bypass-path. To achieve better network performance we proposed a novel method described in the next section.

3.2. Bypass-path selection policy

The goal of the EON Module is to find and allocate resources (set-up a new lightpath as a bypass) to handle the traffic blocked in the IP layer. To solve the RMLSA problem we consider a two-step approach, the algorithm firstly finds a feasible path with determined modulation format, and then allocates a required number of slices N_{bypass}. Presuming the highest modulation formats for selected path we introduce a novel policy named *the most spectral efficient path with the largest slices first* (MSEwLSF) method for first step of the RMLSA solution.

Pseudocode 2 describes the principle of MSEwLSF. For a particular request, that cannot be served at the virtual layer, k-shortest path set is calculated. For each path, the highest feasible modulation format is determined. Let M' represent a set of values describing modulation

formats in terms of bit per symbol (e.g. $M' = 1$ for BPSK, $M' = 2$ for QPSK, $M' = 3$ for QAM, and $M' = 4$ for 16QAM). Then, paths are formed into M'-groups according to the assigned M'. Starting from the group with the highest M' (e.g. 4), inside single group paths are sorted in the decreasing order according to the calculated utilization metric defined in [29] and [30]. Utilization metric denotes "the number of available slices on a path" [30]. Next, ordered paths in a particular group are investigated one by one. If none of the paths in a particular $M' = i$ group cannot provide N_{bypass} slices given by Eq. (1), next $M' = i-1$ group is processed. If the path for a bypass exists, the spectral resources are allocated with the first-fit manner and the EON module ends.

Algorithm 2 the most spectral efficient path with the largest slices first

Require: a demand s, d is rejected in IP
  Calculate n candidate paths s, d and determine highest modulation format M'
  Group paths according to M'
  for all possible M' **do**
    calculate N_{bypass} Eq. (1)
    for paths in increasing order of metric **do**
      if exists N_{bypass} hidden resources are sufficient **then**
        Setup new bypass for service request blocked in IP
        break
      end if
    end for
  end for
  Update network state

To sum up, MSEwLSF analyzes spectrum utilization of paths belonging to the same group of modulation format. The path utilization takes into consideration dynamic changes of spectrum occupancy. Therefore, slices allocated for the bypasses can be spread over the network. As a result, the network load is balanced in the whole network [29–31]. Considering group of paths of one modulation format ensures that the calculated N_{bypass} is the same as for SPF. The goal of the MSEwLSF method is to achieve lower bandwidth blocking probability than the SPF method thanks to the more even resource occupation in the network.

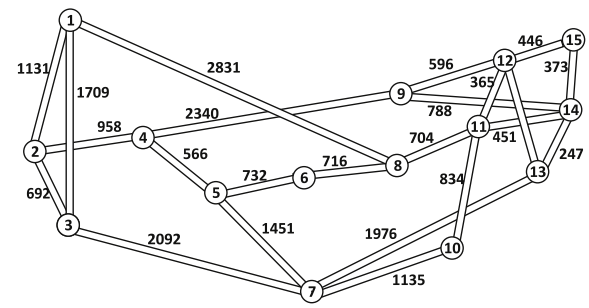
4. Simulation environment

Performance of the bypass-based routing methods in IP-over-EON architecture was assessed throughout simulations performed in two network topologies. We focus on dynamic scenarios, where unexpected traffic bursts might occur. The following metrics were selected as a measure of the routing methods performance:

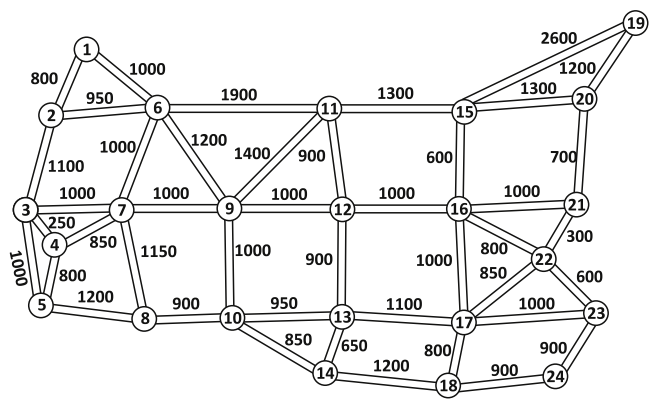
- Bandwidth blocking probability (BBP). The BBP is defined as the total bandwidth of all blocked demands divided by the total bandwidth of all demands (accepted or rejected).
- BBP reduction gain. The gain is defined as a difference between BBP obtained for non-bypass and corresponding bypass scenarios normalized by the BBP in non-bypass scenario. Expressed in percentage, it expresses the potential improvement in terms of BBP reduction by applying bypasses.
- The average number of hops of all accepted demands.
- The overall spectrum occupation. It is total amount of resources occupied by bypasses and reserved (fixed) for the IP layer.

Obtained results were compared with reference scenario assuming that bypass mechanism is not available.

Two considered reference network topologies are NSF (15 nodes, 46 directed links) and UBN (24 nodes, 86 directed links) and are presented in Figs. 2(a) and 2(b) respectively along with distances between nodes. For each network, topologies in the IP and optical layers are the same.



(a) NSF



(b) UBN

Fig. 2. Network topologies used in simulations with marked the distances in kilometers.

Table 1
Simulation parameters for the optical layer.

Parameter	Value
Total spectrum available per fiber	4 THz
Number of slices per fiber	320
Width of slice granularity (Δ_{slice})	12.5 GHz
Guard band (GB)	1

This means that each network node comprises one high-capacity router and one flex-grid switch.

For the sake of analysis, the C-Band (4 THz) of each fiber was assumed to be divided into 320 frequency slices of 12.5 GHz each [8]. One slice was set as a guard-band to separate adjacent optical transmissions. An LP consists of a number of slices (with additional guard-band) and utilizes certain modulation format. Table 1 summarizes parameters related to the optical spectrum.

Four modulation formats were considered in simulations: BPSK, QPSK, 8QAM, and 16QAM. Based on transmission model presented in [32], we decided to use the parameters as shown in Table 2, that describes parameters for modulation formats including transmission reach and bitrate per slice for each modulation format. The same assumptions are taken in e.g. [29,30,33,34], and our previous work [31]. The applied transmission distances allow to set-up long bypasses without regeneration in the networks.

Each directed virtual link was created by the LP, which occupied N_{IP} number of adjacent slices. The following values of N_{IP} were considered:

- bypass case(a): $N_{IP} = 160$

Table 2
Transmission reach and supported bit rate per slice for various modulation formats [29,30,33,34].

Modulation format	Reach	Bitrate
BPSK ($M = 1$ b/s/Hz)	9600 km	12.5 Gbit/s
QPSK ($M = 2$ b/s/Hz)	4800 km	25 Gbit/s
8QAM ($M = 3$ b/s/Hz)	2400 km	37.5 Gbit/s
16QAM ($M = 4$ b/s/Hz)	1200 km	50 Gbit/s

- bypass case(b): $N_{IP} = 200$,
- bypass case(c): $N_{IP} = 240$,
- bypass case(d): $N_{IP} = 280$,
- non-bypass (reference) case: $N_{IP} = 320$.

Then the capacity of a virtual link C_{VL} comprising N_{IP} slices can be calculated using the following equation:

$$C_{VL} = (N_{IP} - GB) * M * \Delta_{slice} \tag{2}$$

where: GB is the number of slices used for the guard-band; M is the spectral efficiency of the modulation format utilized by LP; and Δ_{slice} denotes the width of a slice.

Utilizing the SDN concept both bypass and reference cases can be implemented. Nevertheless, non-bypass could also be implemented in traditional network without SDN capabilities. Simultaneously, in the IP layer the OSPF protocol was used for the routing purposes. To avoid saturation of links, the congestion threshold *th* was introduced. If the usage of a particular link's capacity is below or equal to the *th* then virtual layer handles arriving demands, otherwise bypass mechanism utilizes hidden resources. Based on numerous simulation experiments the *th* was set to 0.7 of the link capacity. Maximum $k = 10$ shortest paths were considered for both SPF and MSEwLSF path selection algorithms in the optical layer. To simplify calculations, sets of candidate paths were computed in the initialization phase.

During simulations, two types of traffic were assumed. First one is a long-lived background traffic between each pair of nodes with bitrate equal to 200 Gb/s for the NSF topology and 80 Gb/s for the UBN topology. The second traffic type is a dynamic inter-DC traffic. The former traffic was always served in the IP layer, the later, can be server in IP or via bypasses. Localization of data centers in the network was determined according to the topology-based method. Hence data centers were associated with nodes with the highest nodal degree in the network [35]. For each pair of data centers demands were uniformly distributed between 50 Gb/s and 1 Tb/s with a 50 Gb/s step (with average value of 525 Gb/s).

Inter-DC traffic demands arrive one by one to the network with an exponentially distributed inter-arrival time and mean value *iat*. The holding time for each request is also modeled using exponential distribution but with mean value *ht*. To simulate different conditions of the traffic load computed as *ht/iat* Erlangs, the mean value of *ht* was changed in a step manner, and simultaneously, value of *iat* was kept constant. For each step of the offered load 10^5 demands were generated. After 5000 demands system reached its steady state, and then an average value was computed and taken as a result. For each scenario, simulation was repeated 30 times and 95% confidence intervals were calculated assuming normal distribution. All experiments were conducted in the OMNeT++ discrete event simulation environment [36].

5. Simulation results

In this section, we present experimental results and discuss the performance of elastic optical bypasses in SDN-based multilayer networks. Especially, we compare performance of bypass-based methods in relation to non-bypass reference scenario. The performance indicators are divided into two groups. The former group is related to BBP, the latter is related to resource utilization including both number of hops in the IP layer as well as overall optical resources. The efficiency of the proposed bypass-based mechanisms was validated throughout numerous simulations performed in two network topologies.

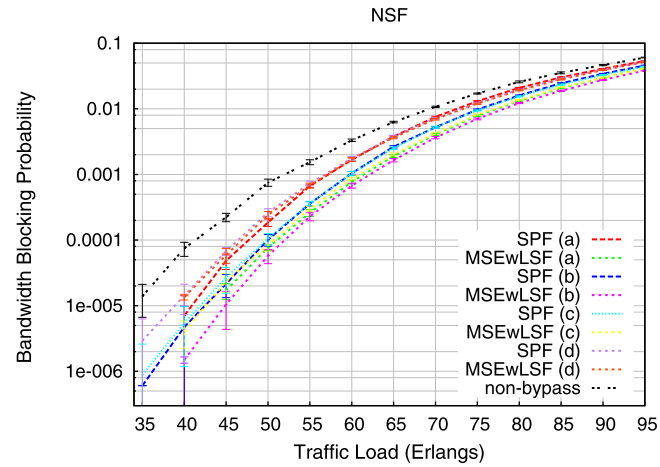


Fig. 3. Simulation results for all bypass cases and non-bypass case in NSF.

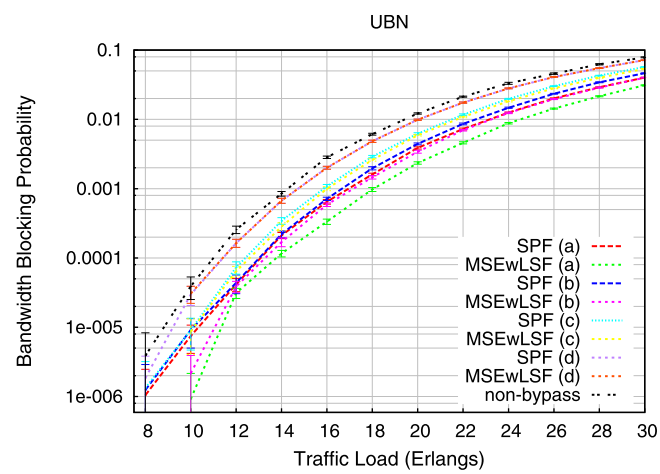


Fig. 4. Simulation results of BBP vs. in function of traffic load for all bypass cases and non-bypass case in UBN.

5.1. BBP metrics

First performance indicator (BBP) for all of the strategies in function of traffic load is given in Fig. 3 (for NSF) and in Fig. 4 (for UBN), whereas Tables 3 and 4 show the results of the BBP reduction gain for NSF and UBN, respectively.

Based on Figs. 3 and 4 the following conclusions can be drawn for both networks. Non-bypass provides the worst performance in terms of BBP when compared to all bypass-based mechanisms. In other words, all bypass-based mechanisms provide lower BBP compared to non-bypass for both networks. That is because, in the non-bypass case, only a single path is utilized to handle traffic between a pair of nodes in the IP layer. Thus, there is no possibility to omit congested links. In contrast, bypasses can be independently set-up and released to provide additional lightpaths to avoid overloaded primary paths. Bypasses give the opportunity to consider various paths for sending traffic between nodes in networks.

Assuming the same amount of hidden resources, detailed analyses of the results for SPF and MSEwLSF show that MSEwLSF provides lower BBP compared to SPF. This is because MSEwLSF introduces load-balancing to optimize lightpaths for bypasses. Thus, MSEwLSF can

handle more bandwidth requests compared to SPF. Furthermore, if MSEwLSF is applied, the first blocking event occurs for heavier traffic than for SPF. This gain can also be observed, when the non-bypass case is compared to MSEwLSF for whichever case of hidden resources. For example, considering the case (a) of hidden resources in NSF (see Fig. 3), the first blocking event occurs for MSEwLSF and SPF under load of 45 Erlangs and 40 Erlangs, respectively. Also for cases (b)(c)(d) the first rejection is observed for MSEwLSF under load of 40 Erlangs, while for SPF under 35 Erlangs. For non-bypass scenario the first request is blocked under load of 35 Erlangs.

Similar conclusions can be drawn based on the results for UBN (see Fig. 4). For all MSEwLSF cases the first demand rejection occurs under load of 10 Erlangs, whereas blocking requests appear earlier if SPF is applied or non-bypass scenario. MSEwLSF introduces the allocation policy which spreads traffic over a network. For cases (a) and (b) effectiveness of MSEwLSF is the most noticeable when network resources are sufficient to allocate all the required bypasses (up to 10 Erlangs). Simultaneously, the BBP observed for MSEwLSF cases (a) and (b) is rapidly increasing for traffic load greater than approx. 10 Erlangs, especially between 10 and 12 Erlangs. This effect results from higher blocking being the consequence of longer lightpaths. Spectrum tends to get more occupied with increasing traffic load and the possibility to successfully establish lightpaths decreases. Moreover, there is a need to accommodate longer lightpaths for bypasses which further increases amount of allocated spectral bandwidth (as mentioned in Section 3.1, Eq. (1)).

Additionally, to provide more detailed analysis the BBP reduction gain introduced by bypasses is summarized in Tables 3 and 4 for NSF and UBN networks, respectively. The gain is presented in function of traffic load, amount of hidden resources and path-selection policy used for bypasses. For example, the gain equal to 50% means that introducing bypasses allowed to reduce BBP by 50%. According to the results, the implementation of bypasses can reduce BBP in range between 8 and 100 percents for both network topologies. Assuming the same amount of hidden resources, the data proves that MSEwLSF achieves higher BBP reduction than SPF. This only confirms our previous findings.

Analyzing results presented in Table 3 for consecutive cases (b), (c), and (d), we can conclude that BBP reduction gain is higher when less resources are available for IP layer no matter of load. Another conclusion regards the fact that the best (equal to 100%) gain in the NSF topology is achieved by SPF and MSEwLSF for the number of hidden slices equal to 160 (case (a)). MSFwLSF(a) achieved the best gain for traffic load, which is higher than for SPF(a). The trend of the results for the case (a) will be analyzed in our future studies.

Considering results obtained for UBN (Table 4), it is clearly visible that the BBP reduction gain increases with increasing amount of hidden resources under a given traffic load. This is because increasing the amount of hidden resources allows to set up more bypasses to offload congested virtual links. Application of MSEwLSF can provide up to 100% of gain for load equal to 8 Erlangs.

In the NSF topology (see Fig. 3 and Table 3) the MSEwLSF(b) method offers the lowest blocking probability for traffic load greater than approx. 45 Erlangs. On the other hand, MSEwLSF(a) provides 100% reduction gain for the heaviest traffic load in the NSF topology. In the UBN topology (see Fig. 4 and Table 4) MSEwLSF(a) achieves the lowest BBP compared to all other strategies. Based on the obtained results for this part of the experiment, it is seen that the best performance of reservation of 160 slices for the MSEwLSF policy in one network topology does not guarantee the same results in terms of the reduction off BBP in another network. Those trends will be thoroughly analyzed in our future studies.

5.2. Resource utilization metrics

The average number of hops traversed in IP is analyzed as a third metric while the overall spectrum occupation is fourth, and the last discussed metric.

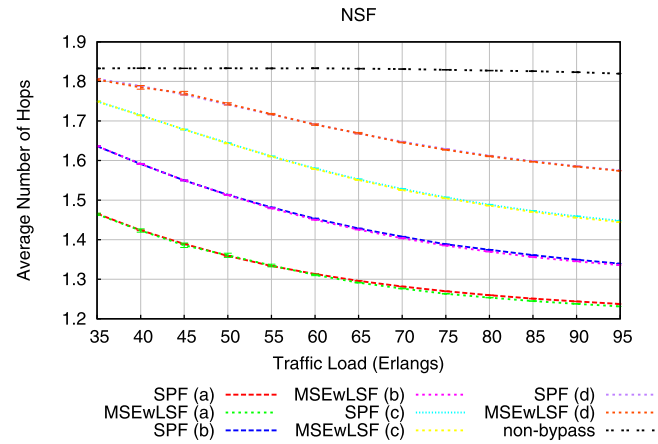


Fig. 5. Average number of hops in function of traffic load for bypass mechanisms and non-bypass case in NSF.

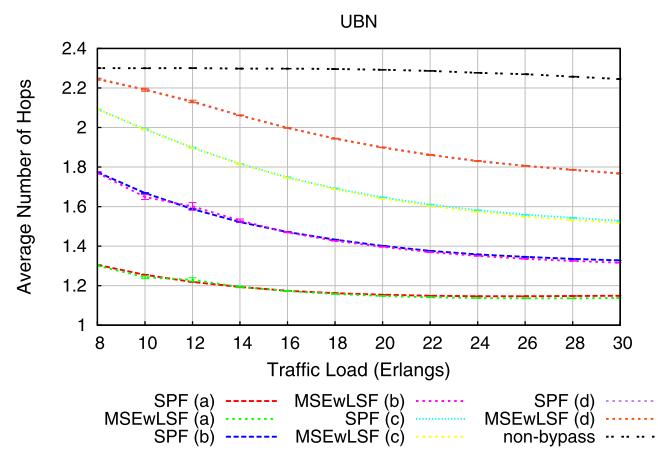


Fig. 6. Average number of hops vs. traffic load for bypass mechanisms and non-bypass case in UBN.

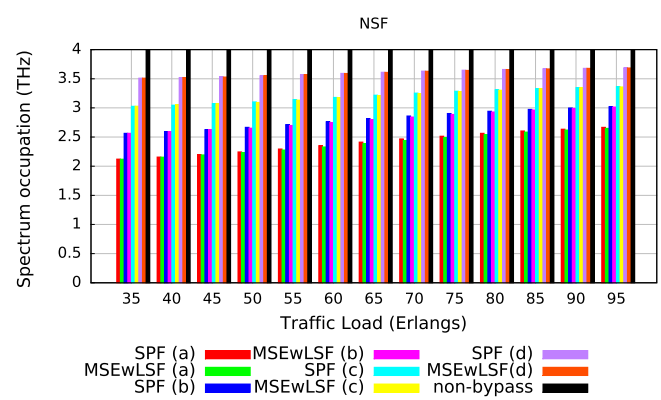


Fig. 7. Overall spectrum occupation for bypass mechanisms and non-bypass case in NSF.

The third performance indicator for all the strategies is given in Fig. 5 for NSF and in Fig. 6 for UBN. All bypass-based mechanisms provide shorter IP routes when compared to non-bypass. In the proposed bypass scenarios, the length of bypasses is one hop. In other words, a bypass between end nodes is set up transparently for the IP layer, thus less hops are used. The more resources are reserved for the bypass-based mechanisms, the less hops are utilized in the IP layer. When traffic load increases, bypasses occur more frequently. Thus the number

Table 3
BBP gains of different bypass mechanisms in comparison to non-bypass in NSF.

Traffic Load (Erlangs)	35	40	45	50	55	60	65	70	75	80	85	90	95
SPF(a)	100%	90.5%	78.3%	75.3%	56.7%	49.5%	39.8%	29.8%	23.6%	19.1%	14.5%	12.1%	11.6%
SPF(b)	95.7%	93.7%	90.3%	86.6%	76.8%	68.7%	60%	51.2%	44.8%	40%	33.9%	29.1%	27.1%
SPF(c)	93.6%	92.7%	87.9%	86%	76.6%	68%	58%	51%	42.9%	37.8%	30.7%	26.3%	24.5%
SPF(d)	79%	80.8%	69.6%	65%	52.5%	46.9%	39.9%	33.3%	28.4%	24.5%	18.3%	15.1%	13.4%
MSEwLSF(a)	100%	100%	92.4%	89.8%	83.1%	76.9%	69.7%	62%	54.1%	48.7%	41.7%	36%	32.1%
MSEwLSF(b)	100%	98%	95.3%	92.4%	85.1%	79.6%	73.7%	66.1%	58.9%	52.6%	46.9%	40.4%	36.8%
MSEwLSF(c)	100%	94.6%	89.4%	88.9%	80.6%	74.2%	67.6%	60.5%	52.3%	47.2%	40.2%	35.9%	32%
MSEwLSF(d)	100%	81.8%	73.4%	67.9%	56.1%	48.7%	42%	35%	29.9%	25.6%	20.8%	16%	14.2%

Table 4
Comparison of BBP gains in UBN.

Traffic Load (Erlangs)	8	10	12	14	16	18	20	22	24	26	28	30
SPF(a)	90.2%	83.8%	80.9%	75%	77.2%	73.7%	68.2%	65.9%	62.2%	56.1%	53.4%	49%
SPF(b)	83.8%	80.9%	74.9%	73.9%	68.2%	67.7%	63.6%	59.6%	55.6%	48.7%	45%	41%
SPF(c)	83.7%	76.7%	71.5%	59.4%	61.8%	52.4%	49%	45.2%	40.3%	34%	31.4%	27.5%
SPF(d)	72.3%	31.9%	29.4%	21.7%	20.9%	20.7%	18.8%	17.7%	15.6%	12%	10.5%	8.7%
MSEwLSF(a)	100%	97.6%	88.2%	87.8%	86.3%	84%	80.7%	78%	73.4%	68.6%	65.4%	60.5%
MSEwLSF(b)	100%	94.5%	84.9%	80%	79.3%	76.1%	71.9%	67.3%	62.6%	57.1%	53.9%	49.1%
MSEwLSF(c)	100%	77.8%	75%	66.5%	64.8%	57.4%	51.5%	49.2%	45.1%	38.7%	36.3%	31.6%
MSEwLSF(d)	100%	36.1%	34.1%	30.8%	24.3%	22.6%	19.5%	17.9%	17%	12.2%	11.2%	8.8%

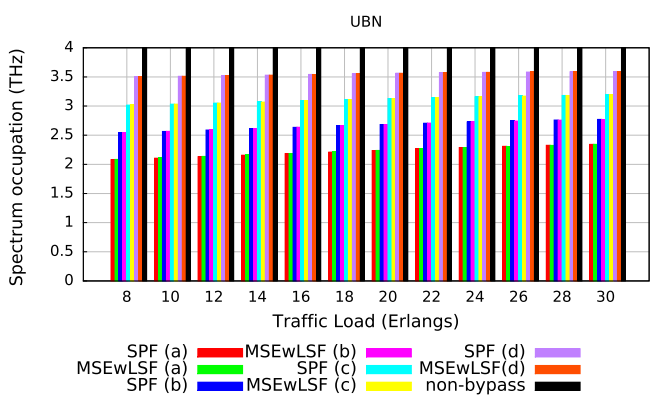


Fig. 8. Overall spectrum occupation for bypass mechanisms and non-bypass case in UBN.

of hops in IP slightly decreases for bypass-based methods. The average number of hops in IP is almost the same for MSEwLSF and SPF for the same amount of hidden resources.

Finally, we report on the overall spectrum occupation achieved by different mechanisms. In Figs. 7 and 8 we present the overall spectrum occupation for NSF and UBN, respectively. All bypass-based mechanisms achieve lower spectrum occupation when compared to non-bypass cases. Non-bypass utilizes all spectrum (4 THz) and the level of spectrum occupation is constant during simulations. Furthermore, it can be observed that the obtained spectrum occupation increases with increasing traffic intensity for bypass cases. It results from the fact that more bypasses are set-up to serve requests. Therefore, hidden resources are utilized more frequently. On the other hand, the spectrum is allocated for longer paths, and thus the less effective modulation format must be applied compared to short ones. Nevertheless, levels of spectrum occupation are still lower when bypasses are introduced.

What we can also observe is fact that case (a) for both SPF and MSEwLSF methods outperforms other cases. It is an intuitive consequence of the fact that overall spectrum occupation is the sum of resources fixed for the IP layer and the amount of resources utilized to establish bypasses. Based on the results, it can be noticed that the spectrum occupation is almost the same for MSEwLSF and SPF for the same amount of hidden resources. For the assuming case of hidden resources the MSEwLSF method utilizes almost the same amount of spectrum, despite the fact that MSEwLSF sends more traffic than SPF. This confirms that the proposed MSEwLSF utilizes optical resources in more effective way. This conclusion is consistent with the conclusion presented in [29–31].

To sum up the results, we note that the average bandwidth blocking is lower when bypasses are used. It stems from the fact that in a non-bypass case, only single path in the IP layer is considered to handle particular request between a given pair of nodes. Thus, there is no possibility to omit congested links. In all scenarios of hidden resources, using bypasses allows to send more traffic with a lower number of hops in terms of O/E/O conversions compared to non-bypass. Less O/E/O conversions may result in lower delay and lower energy consumption. Moreover, the bypasses reduce the overall spectrum occupation in multilayer networks. Additionally, the MSEwLSF method provides lower BBP with almost the same number of hops when compared to SPF for a given number of hidden slices. MSEwLSF achieves lower BBP than SPF, but the number of hops and the level of spectrum occupation are the same in both scenarios. This fact clearly proves that the proposed MSEwLSF algorithm achieves better performance than SPF.

6. Conclusion

This paper explains the concept and verifies advantages of elastic optical bypasses handling inter-DC traffic in the IP-over-EON architecture. The main idea is to route traffic through IP paths, but when traffic congestion occurs, new LPs are established using hidden resources in the optical layer. In order to achieve load-balancing during bypass allocation, a novel bypass-path selection policy has been introduced to determine bypass-paths. The presented mechanisms have been implemented and evaluated using numerical simulations in dynamic scenarios performed in two reference topologies. Moreover, the performance of mechanisms has been studied depending on the amount of resources available for virtual links established over elastic optical networks.

Analysis of the obtained results has shown that both bypass path selection algorithms (SPF and MSFwLSF) reduce BBP in comparison to the non-bypass approach. For example, all bypass approaches clearly outperform standard networks in BBP providing improvement at the level between 8% and 100%. Moreover, the proposed MSFwLSF algorithm performs better than SPF in terms of BBP reduction. Additionally, MSFwLSF can serve more traffic until first blocking event appears. Simulation results also reveal that, compared to non-bypass, the proposed bypasses provide lower resource utilization including both number of hops in the IP layer as well as overall spectrum occupation.

In conclusion, it was demonstrated that elastic optical bypasses are suitable for inter-DC networks in which highly unpredictable traffic spikes can be expected. Future works will investigate bypass mechanisms in IP-over-EON architectures with regenerators for different network topologies and data center locations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Cisco, Cisco visual networking index: forecast and methodology, 2016–2021, Forecast Methodol. (2015) 22, http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.pdf.

[2] J. Domżał, Z. Duliński, J. Rząsa, P. Gawłowicz, E. Biernacka, R. Wójcik, Automatic hidden bypasses in software-defined networks, J. Netw. Syst. Manag. (2016) 1–24, http://dx.doi.org/10.1007/s10922-016-9397-5.

[3] P. Boryło, J. Domżał, R. Wójcik, Survivable automatic hidden bypasses in software-defined networks, Comput. Netw. 133 (2018) 73–89, http://dx.doi.org/10.1016/j.comnet.2018.01.022.

[4] J. Domżał, R. Wójcik, E. Biernacka, Efficient and reliable transmission in Flow-Aware Networks – an integrated approach based on SDN concept, in: ICNC 2017 International Conference on Computing, Networking and Communications, Silicon Valley, CA, USA.

[5] O. Gerstel, M. Jinno, A. Lord, S.J.B. Yoo, Elastic optical networking: a new dawn for the optical layer? IEEE Commun. Mag. 50 (2) (2012) s12–s20, http://dx.doi.org/10.1109/MCOM.2012.6146481.

[6] M. Jinno, Elastic optical networking: roles and benefits in beyond 100-Gb/s era, J. Lightwave Technol. 35 (5) (2017) 1116–1124, http://dx.doi.org/10.1109/JLT.2016.2642480.

[7] A. Lord, P. Wright, A. Mitra, Core networks in the flexgrid era, J. Lightwave Technol. 33 (5) (2015) 1126–1135, http://dx.doi.org/10.1109/JLT.2015.2396685.

[8] ITU-T, Spectral grids for WDM applications: DWDM frequency grid (G.694.1), ITU-T Recommendation G.694.1.

[9] I.B. Djordjevic, B. Vasic, Orthogonal frequency division multiplexing for high-speed optical transmission., Opt. Express 14 (9) (2006) 3767–3775, http://dx.doi.org/10.1364/OE.14.003767.

[10] G. Zhang, M. De Leenheer, A. Morea, B. Mukherjee, A survey on ofdm-based elastic core optical networking, IEEE Commun. Surv. Tutor. 15 (1) (2013) 65–87, http://dx.doi.org/10.1109/SURV.2012.010912.00123.

[11] I. Tomkos, S. Azodolmolky, J. Solé-Pareta, D. Careglio, E. Palkopoulou, A tutorial on the flexible optical networking paradigm: state of the art, trends, and research challenges, Proc. IEEE 102 (9) (2014) 1317–1337, http://dx.doi.org/10.1109/JPROC.2014.2324652.

[12] K. Christodoulopoulos, I. Tomkos, E.A. Varvarigos, Elastic bandwidth allocation in flexible OFDM-based optical networks, J. Lightwave Technol. 29 (9) (2011) 1354–1366, http://dx.doi.org/10.1109/JLT.2011.2125777.

[13] T. Tanaka, A. Hirano, An in-operation ip-over-optical network planning method that supports unpredictable ip traffic transitions, Eur. Conf. Opt. Commun. ECOC (2014) 2–4, http://dx.doi.org/10.1109/ECOC.2014.6963949.

[14] T. Tanaka, T. Inui, A. Kadohata, W. Imajuku, A. Hirano, Multiperiod ip-over-elastic network reconfiguration with adaptive bandwidth resizing and modulation, J. Opt. Commun. Netw. 8 (7) (2016) A180, http://dx.doi.org/10.1364/JOCN.8.00A180.

[15] C. Kyriakopoulos, G.I. Papadimitriou, P. Nicopolitidis, E. Varvarigos, Energy-efficient lightpath establishment in backbone optical networks based on ant colony optimization, J. Lightwave Technol. 34 (23) (2016) 5534–5541, http://dx.doi.org/10.1109/JLT.2016.2623678.

[16] V. Gkamas, K. Christodoulopoulos, E. Varvarigos, Energy-aware multi-layer flexible optical network operation, in: 2015 23rd International Conference on Software, Telecommunications and Computer Networks, SoftCOM, 2015, pp. 16–21, http://dx.doi.org/10.1109/SOFTCOM.2015.7314088.

[17] Y. Hong, X. Hong, S. He, J. Chen, Hybrid routing and adaptive spectrum allocation for flex-grid optical interconnects, IEEE/OSA J. Opt. Commun. Networking 10 (5) (2018) 506–514, http://dx.doi.org/10.1364/JOCN.10.000506.

[18] D.M. Divakaran, S. Hegde, R. Srinivas, M. Gurusamy, Dynamic resource allocation in hybrid optical-electrical datacenter networks, Comput. Commun. 69 (2015) 40–49, http://dx.doi.org/10.1016/j.comcom.2015.07.008.

[19] M. Savi, C. Rožić, C. Matrakidis, D. Klonidis, D. Siracusa, I. Tomkos, Benefits of multi-layer application-aware resource allocation and optimization, in: 2017 European Conference on Networks and Communications, EuCNC, 2017, pp. 1–5. http://dx.doi.org/10.1109/EuCNC.2017.7980661.

[20] I. Tomkos, Ćiril. Rožić, M. Savi, P. Sköldström, V. Lopez, M. Chamania, D. Siracusa, C. Matrakidis, D. Klonidis, O. Gerstel, Application aware multilayer control and optimization of elastic WDM switched optical networks, in: 2018 Optical Fiber Communications Conference and Exposition, OFC, vol. Part F84-O, 2018, pp. 1–3.

[21] L. Velasco, A. Asensio, J.L. Berral, E. Bonetto, F. Musumeci, V. López, Elastic operations in federated datacenters for performance and cost optimization, Comput. Commun. 50 (2014) 142–151, http://dx.doi.org/10.1016/j.comcom.2014.03.004.

[22] H. Yang, J. Zhang, Y. Zhao, Y. Ji, J. Wu, X. Yu, J. Han, Y. Lee, Global resources integrated resilience for software defined data center interconnection based on IP over elastic optical network, IEEE Commun. Lett. 18 (10) (2014) 1735–1738, http://dx.doi.org/10.1109/LCOMM.2014.2353633.

[23] H. Yang, Y. Zhao, J. Zhang, L. Cheng, Y. Ji, J. Wu, J. Han, Y. Lin, Y. Lee, Multi-stratum resources resilience in software defined data center interconnection based on IP over elastic optical networks, Photonic Netw. Commun. 28 (1) (2014) 58–70, http://dx.doi.org/10.1007/s11107-014-0440-8.

[24] S. Fichera, R. Martínez, B. Martini, M. Gharbaoui, R. Casellas, D.R. Vilalta, R. Muñoz, P. Castoldi, Latency-aware resource orchestration in SDN-based packet over optical flexi-grid transport networks, IEEE/OSA J. Opt. Commun. Networking 11 (4) (2019) B83–B96, http://dx.doi.org/10.1364/JOCN.11.000B83.

[25] E. Biernacka, J. Domżał, R. Wójcik, Dynamic sliceable optical bypasses in SDN-based networks, in: 2017 19th International Conference on Transparent Optical Networks, ICTON, 2017, pp. 1–4, http://dx.doi.org/10.1109/ICTON.2017.8024962.

[26] Ć. Rožić, D. Klonidis, I. Tomkos, A survey of multi-layer network optimization, in: 2016 International Conference on Optical Network Design and Modeling, ONDM, 2016, pp. 1–6, http://dx.doi.org/10.1109/ONDM.2016.7494053.

[27] G. Zhang, M. De Leenheer, B. Mukherjee, Optical traffic grooming in ofdm-based elastic optical networks [invited], IEEE/OSA J. Opt. Commun. Networking 4 (11) (2012) B17–B25, http://dx.doi.org/10.1364/JOCN.4.000B17.

[28] A. Castro, L. Velasco, M. Ruiz, J. Comellas, Single-path provisioning with multi-path recovery in flexgrid optical networks, in: 2012 IV International Congress on Ultra Modern Telecommunications and Control Systems, 2012, pp. 745–751, http://dx.doi/org/10.1109/ICUMT.2012.6459763.

[29] L. Zhang, W. Lu, X. Zhou, Z. Zhu, Dynamic RMSA in spectrum-sliced elastic optical networks for high-throughput service provisioning, in: Computing, Networking and Communications (ICNC), 2013 International Conference on, 2013, pp. 380–384, http://dx.doi.org/10.1109/ICCNC.2013.6504113.

[30] Z. Zhu, W. Lu, L. Zhang, N. Ansari, Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing, J. Lightwave Technol. 31 (1) (2013) 15–22, http://dx.doi.org/10.1109/JLT.2012.2227683.

[31] E. Biernacka, J. Domżał, R. Wójcik, Investigation of dynamic routing and spectrum allocation methods in elastic optical networks, Int. J. Electron. Telecommun. 63 (1) (2017) 85–92, http://dx.doi.org/10.1515/eletel-2017-0012.

[32] A. Bocoi, M. Schuster, F. Rambach, M. Kiese, C.-a. Bunge, B. Spinnler, Reach-dependent capacity in optical networks enabled by OFDM, in: 2009 Conf. Opt. Fiber Commun. - incudes post deadline Pap., 2009, pp. 25–27, http://dx.doi/org/10.1364/OFC.2009.OMQ4.

[33] F. Shirin Abkenar, A. Ghaffarpour Rahbar, Study and analysis of routing and spectrum allocation (RSA) and routing, modulation and spectrum allocation (RMSA) algorithms in elastic optical networks (EONs), Opt. Switch. Netw. 23 (2017) 5–39, http://dx.doi.org/10.1016/j.osn.2016.08.003.

[34] A. Agrawal, V. Bhatia, S. Prakash, Spectrum efficient distance-adaptive paths for fixed and fixed-alternate routing in elastic optical networks, Opt. Fiber Technol. 40 (October 2017) (2018) 36–45, http://dx.doi.org/10.1016/j.yofte.2017.11.001.

[35] R. Goścień, K. Walkowiak, Comparison of different data center location policies in survivable elastic optical networks, in: 2015 7th International Workshop on Reliable Networks Design and Modeling, RNDM, 2015, pp. 48–55, http://dx.doi/org/10.1109/RNDM.2015.7324308.

[36] OMNET++, http://www.omnetpp.org. (Accessed September 2018).