Impact of Lightpath Selection on End-to-End Service Orchestration in Disaggregated Optical Networks

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***Abstract*—This paper investigates the role of orchestration in lightpath selection to enable end-to-end service provisioning in disaggregated optical networks. As these networks redefine traditional optical infrastructures, the dynamic allocation of resources becomes of paramount importance to meet the escalating demands of data-intensive applications. Lightpath selection, representing the physical routes in the optical network, emerges as a pivotal factor shaping overall network performance. Through a focused exploration of the relationship between lightpath selection and service orchestration, this paper proposes a modeling approach to design resources by evidencing what is new in the Software Defined Networking (SDN) process with respect to traditional optical networks with reference to a layered representation. An analytical procedure based on classical blocking theory is presented to calculate an upper bound on the blocking introduced by Optical-Electrical-Optical (OEO) wavelength conversion. Call blocking in the range of 10^{-4} is shown as achievable also for large size networks providing a suitable number of wavelength converters made available by network-wide to the orchestrator as virtualized resources. Perspective research in the application of traffic theory to abstracted resources is outlined as a conclusion.**

Keywords: Service Orchestration, Software-Defined Networking, Optical Networks, Lightpath selection, Traffic model

I. Introduction

In the ever-evolving landscape of telecommunications, the demand for high-capacity and low-latency end-to-end services continues to surge, driven by the relentless growth of data-intensive real-time applications. Disaggregated optical networks have emerged in the last few years as a viable solution to meet these escalating demands, by decoupling the traditional monolithic optical infrastructure into modular and interoperable components. This paradigm shift enables network operators to dynamically allocate resources, optimize performance, and enhance scalability, ultimately fostering a more flexible and efficient network ecosystem.

Central to the success of disaggregated optical networks is the ability to perform effective end-to-end service orchestration, managing the available network resources while meeting service-level agreements. Within this context, the selection of lightpaths (i.e., the physical routes that data traverses through the optical network) becomes a pivotal element. Indeed, providing efficient connectivity is one of the main tasks for the orchestration system, as the strategic choice of lightpaths significantly influences the overall performance of the network, directly impacting the quality of services delivered to end-users.

End-to-end service orchestration has been investigated in the literature in recent years as an overall theme. Many innovations and frameworks have been proposed for the automated provisioning of services in a multi-domain context, including by the 5Growth project [1], which proposed the innovations required to meet 5G end-to-end service requirements while it was being standardized, or the ACROSS project [2], which presents a platform for end-to-end service orchestration across distributed softwarized domains. A conceptual architecture for the same purpose is proposed in [3]. Although these works implicitly leverages the optical transport domain, they do not consider its inherent features explicitly.

Conversely, in [4], a strategy for the provisioning of services by considering the specific characteristics of involved optical network segments is presented, and further specified with the addition of latency and availability constraints. In this context, the advent of disaggregation in optical networks, the subsequent adoption of Software Defined Networking (SDN) and the recent technological advances in the manufacturing of coherent optical transceivers are allowing the implementation of lightpath provisioning with an unprecedented level of flexibility [5], [6].

This paper aims at studying the interplay between optical resource orchestration and service provisioning in the process of lightpath selection over disaggregated optical networks. To this end, a layered architecture is adopted to describe the role of control and orchestration in the SDN context with abstracted resource selection. The main assumption here is that the orchestrator operates on abstractions of the optical devices available in the network, such as switches, their interfaces, the wavelengths they support, and wavelength converters. Modeling these resources through their functional and performance characteristics, i.e., through the features of interest to the orchestrator, is an aspect scarcely investigated in literature. So a traffic model that considers abstracted resources distributed across the network is defined to support the orchestrator in configuring the lightpaths according to end-to-end service requests and related requirements and constraints.

The paper is organized as follows. In Section I orchestration of lightpath selection according to resource availability and service requirement is introduced. In Section III a layered description of functionalities and relationships among orchestration system components is described. In Section IV a methodology for the dimensioning of wavelength conversion resources is formulated. Section V presents results in terms of blocking introduced by limited wavelength conversion availability. The conclusions of the paper are drawn in Section VI.

II. ORCHESTRATION OF LIGHTPATH SELECTION

The provisioning of an end-to-end service involves the orchestration of networking and computing resources possibly spanning over multiple domains. Those elements are regarded as components of the service, and arranged accordingly, based on the requirements that need to be satisfied. The composition of such service functions can be referred to as a Service Function Chain (SFC), i.e., a concatenation of basic functionalities constituting a composite service, spanning across the network domain. Typical examples of service functions include computing elements that perform traffic optimization duties (e.g., load balancing, traffic shaping, etc.) or security tasks (e.g., firewalling, encryption, deep packet inspection).

Concurrently, the deployment of composite services spanning across multiple domains must also necessarily consider the features, benefits, and limitations of the optical transport network. So, as a part of the composition of functions and resources to provide a service, lightpath selection plays a crucial role in enforcing service deployment.

Existing literature reports performance evaluation of SFC deployment (e.g., [7]) with little consideration for inherent features of the optical transport network. However, the transport segment plays a significant role in the deployment of services across geographically distributed domains [8], and should therefore be carefully considered. In fact, in practical scenarios, when configuring connectivity between remote locations, a service orchestrator might have to choose between different options for setting up a lightpath. Such set up consists of finding a concatenation of optical links to connect end points through possibly different transport network resource options. Whereas routing in conventional networks was typically based on shortest path routing, with some flexibility in traffic management represented by load balancing among equivalent paths, disaggregation in optical networks introduces the possibility to offer a set of segments (i.e. abstracted connectivity resources) to the orchestrator, which is then able to compose them into connected lightpaths, according to service requirements.

On the other hand, in the past, several studies evaluated the utilization of wavelength conversion to facilitate the lightpath routing even considering dedicated non-linear optical converters or Optical-Electrical-Optical (OEO) conversion [9], [10]. However, such solutions did not succeed at the commercial level, indeed the first option was discarded due to high cost and low reliability of such non-linear converters; while the second option was discarded due to its implementation complexity at the control plane level (i.e., it requires coordinated configuration of both the IP and optical networks). However, the possible use of OEO conversion should be nowadays reconsidered assuming the existence of advanced orchestration systems and IPoWDM nodes exploiting coherent optical transceiver that strongly simplify the control scenario [11].

Disaggregation in optical networks allows for the consideration of multiple aspects as criteria for path definition. Such criteria allow to characterize the lightpath on a set of performance parameters (e.g., related to the adopted modulation format [12]), which the orchestrator can take into account to shape the connectivity, according to service needs. In addition, the possibility of exploiting processing capability within the network, including the performance of OEO conversion, introduces further flexibility to reach trade-offs in terms of latency, data rate, power consumption, and blocking probability, as discussed in the following.

- **Latency**. Latency refers to the end-to-end delay, spanning from packet transmission at the source to its reception at the destination. It is influenced primarily by physical distance, such as light propagation delay, and is further affected by OEO conversions along the data path. These conversions impact data transparency but facilitate wavelength shifts, reducing blocking rates when establishing a lightpath.
- **Data rate**. The data rate in optical networks is determined by transceiver speed and can vary between interconnected domains. Typically ranging between tens and hundreds Gigabits per second, it is at least one order of magnitude higher than the rate achievable in the electronic domain (e.g., coherent optical transceivers are nowadays available at 400 Gbps and 800 Gbps using the QSFP form factor [11]). However, employing OEO conversion may result in lower data rates.
- **Energy consumption**. Energy consumption is influenced by both hardware and software components along the lightpath, and it depends on the characteristics of the devices which are made available to the orchestrator for optimization. Introducing OEO conversion is expected to increase energy usage.
- **Lightpath setup blocking probability**. The probability of blocking during lightpath setup is mitigated by incorporating wavelength conversion capabilities into the network. OEO conversion at switches enables wavelength shifting, resolving conflicts and facilitating new lightpath establishment.

As discussed, the possibility to use different wavelengths along the lightpath is an important factor that contributes to the success in deploying the requests connected path according to service requirements.

For instance, the orchestrator might need to choose between setting up a lightpath composed of a greater number of segments, but maintaining wavelength continuity, or one consisting of a smaller number of segments, but requiring wavelength conversion in one or more points. This difference is crucial in the possibility to successfully deploy the lightpath satisfying service requirements, as it impacts all of its characteristic features.

In this context, a pivotal role is played by both conceptual and implementative aspects of SDN controllers, which interact with the physical and virtualized devices in the infrastructure and create an abstraction of the underlying topology for the orchestration layer. In the specific case of lightpath setup, SDN controllers are able to provide all the available channels for each pair for each network link in the network, so that the orchestrator can decide how to compose links and possibly include OEO stages for wavelength conversion across the path.

Some degree of independence is left to SDN controllers, for example in case the orchestrator does not need to specify all parameters of a lightpath. The way this is handled by different SDN controllers is a matter of implementation. For instance, the open-source SDN controller distributed by the Open Network Foundation (ONF), i.e.,ONOS [13], assigns frequency bands with a first-fit policy, if not otherwise specified in the connectivity request coming from the orchestrator. Furthermore, if the request does not specify a complete set of segments between two endpoints in the domain of the controller, ONOS applies a shortest path algorithm to determine how to connect the endpoints, with the length of the path defined as the number of crossed switches.

III. Layered system model

End-to-end service provisioning needs appropriate orchestration of optical resources for lightpath establishment to meet quality of service requirements.

Investigation of optical network performance has mainly focused on the availability of node resources and wavelength conversion capability [14], [15]. Disaggregation in optical networks and the advent of SDN introduce a novel approach where optical network resources are perceived by the service orchestrator as software abstractions. Each optical device is characterized based on to its performed functions and the performance parameters relevant to service set-up, such as latency, data rate and energy efficiency, as explained above. This includes OEO converters, which are regarded as abstracted elements that can be incorporated by the orchestrator in the end-to-end connected path. This is independent of their location, i.e., the assumption is not that all optical nodes necessarily have to incorporate an OEO conversion stage. The distribution of OEO converters has an impact on the overall performance, as each time a conversion is required, the traffic needs to be steered through an available converter, adding further contributions to the overall latency and energy consumption.

In Fig. 1 a layered representation of the roles of orchestrator and SDN controllers in relating the optical network infrastructure to end-to-end service provisioning leveraging on abstracted resources is shown.

In particular, through their northbound APIs, SDN controllers expose resource abstractions, each characterized by features relevant to the devices it represents, to the orchestrator. The way these interfaces are implemented (e.g., HTTP REST, gRPC, etc.) and the format of the data they exchange (e.g., JSON, YAML, etc.) is irrelevant as long as the orchestrator supports them.

For the purpose of lightpath selection, abstracted resources represent network nodes, links and OEO converters, with the corresponding represented devices being suitably located and interconnected in the physical infrastructure.

The performed abstraction enhances the flexibility of the whole process, allowing to find the most appropriate solution for end-to-end service deployment.

Based on the knowledge of the available optical links and OEO converters, the orchestrator may choose among multiple alternative paths to establish connectivity across the infrastructure, and the availability of these alternatives depends, in turn, on the total amount of nodes performing switching, the average node degree, and average link delay [16].

A service overlay is enabled on top of the orchestrator, consisting of abstracted elements which represent devices (or sliced portions of them, obtained through virtualization/disaggregation) and links in the underlying infrastructure. The SDN controllers of each domain then take the role of deploying and operating the lightpath, properly setting the resources chosen by the orchestrator in the network infrastructure.

The amount of abstracted resources visible to the orchestrator is a design aspect in this context, and it directly influences performance in relation to resource parameters. For this reason modeling resource behaviour is an important aspect, as explained in the following section for OEO wavelength converters.

IV. Resource dimensioning and performance

Ensuring the effective establishment and ongoing maintenance of a service is closely tied to resource availability and the appropriate selection of the supporting lightpath to fulfill end-to-end service requirements. In this evaluation, the choice of lightpath is considered, based on resource availability, and blocking performance is assessed, when allowing wavelength conversion. This is achieved through OEO conversion, and it is deemed viable only if the additional latency introduced is compliant with the latency constraints imposed by the end-to-end service. The resources considered in the model are the abstracted resources as seen by the orchestrator, which are characterized by their functionalities, including switching and wavelength conversion capabilities, as well as performance metrics, e.g., latency.

Blocking in an optical node comes from two main factors: wavelength blocking and output overflow. The former occurs when there is contention for a specific wavelength on the output interface, when continuity with the input wavelength is enforced. The latter arises when the number of lightpaths needing to be established exceeds the capacity supported by available wavelengths in the node. Wavelength blocking can be

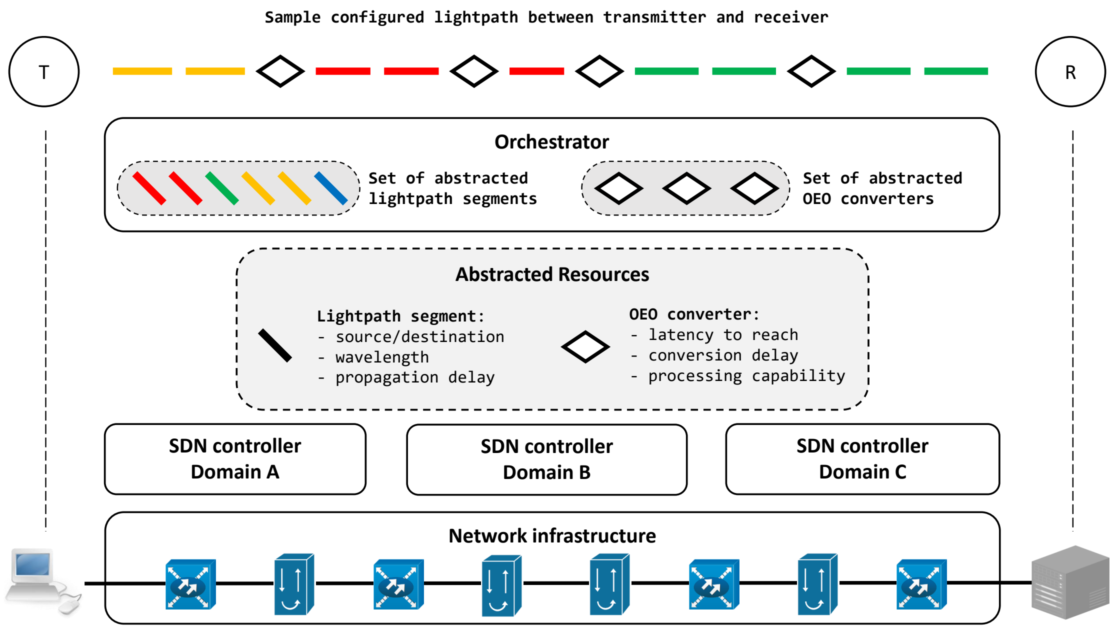

Fig. 1. Layered architecture with SDN abstractions for lightpath selection.

TABLE I
LIST OF VARIABLES OF THE BLOCKING MODEL

List of variables	
A_W	Offered traffic per wavelength
N_S	Number of optical switches
N_I^S	Number of I/O interfaces per optical switch
N_W	Number of wavelengths per interface
N_C	Number of OEO converters in the shared pool

mitigated or solved with wavelength conversion, which, however, contributes to the blocking occurring at the wavelength converter set, in case of unavailability of a sufficient number of converters. Wavelength converters are made available to the orchestrator by means of abstractions operated by the SDN controllers at the network level.

Let us consider the softwarized network $\mathcal{N}$, consisting of virtualized devices and links possibly belonging to different domains, under the control of the orchestrator. In Table I, the variables of the model are listed, namely the lightpath offered traffic per wavelength A_W, the number of wavelengths per switch interface N_W, the number N_I^S of inputs or outputs interfaces of the symmetric optical switches, the number of optical switches N_S in $\mathcal{N}$, and the total number N_C of virtualized OEO wavelength converters available in $\mathcal{N}$, that can be used for wavelength shifting along lightpaths.

The schematic representation of the model is shown in Fig. 2.

Firstly, A_W^B, the traffic blocked due to the unavailability of the wavelength on the output interface of the optical switch is calculated as

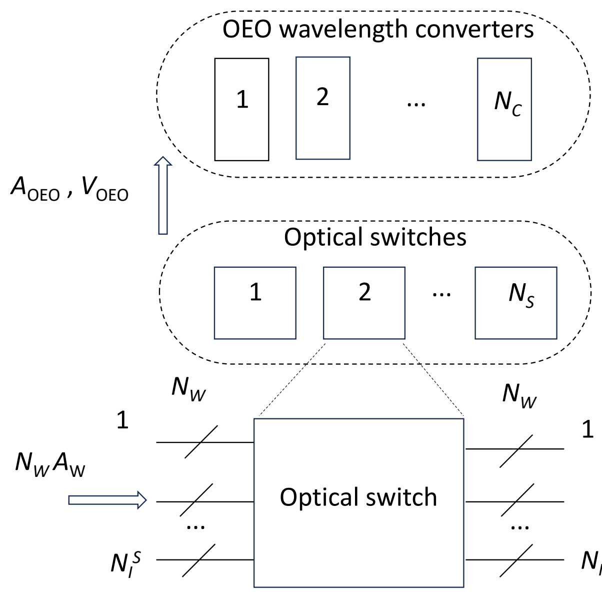

Fig. 2. Schematic representation of the traffic model and variables.

$$A_W^B = A_W \mathcal{B}(1, N_I^S \frac{A_W}{N_I^S}) = A_W \mathcal{B}(1, A_W) \qquad (1)$$

where $\mathcal{B}$ is the Erlang-B Formula [17]. In fact, to maintain wavelength continuity, the contention arises on a single wavelength of the addressed output interface that is loaded with the traffic coming on that wavelength from the N_I^S input interfaces with a fraction $\frac{1}{N_I^S}$ of the overall traffic. This blocked traffic A_W^B, as known by traffic theory [18], exhibits non-Poisson behavior. Assuming the contributing wavelengths as independent, which is reasonable within $\mathcal{N}$, the total traffic A^B_{tot} blocked in $\mathcal{N}$ and its variance V^B_{tot} are

$$A^B_{tot} = N_S N_W N^S_I A^B_W = N_S N_W N^S_I A_W \mathcal{B}(1, A_W) \quad (2)$$

and

$$V^B_{tot} = N_S N_W N^S_I A^B_W \left(1 - A^B_W + \frac{A_W}{1 - A_W + A^B_W + 1}\right) \quad (3)$$

respectively.

In practice, only a portion of the traffic characterized by mean the value A^B_{tot} and variance V^B_{tot} is sent to the converters, i.e., the portion that does not exceed the load on the switch interfaces [14], that is

$$A_{OEO} = A^B_{tot} - N_S N_W N^S_I A_W \mathcal{B}(N_W, N_W A_W) \quad (4)$$

To apply the Fredericks' theory [18] and the Lindberger [19] solution methodology, the factor denoted as z is introduced:

$$z = \frac{V_{OEO}}{A_{OEO}} \quad (5)$$

As an approximation, the assumption $V_{OEO} = V^B_{tot}$ is made, representing an upper bound on the variance. In fact $V^B_{OEO} < V^B_{tot}$, as a consequence of the subtraction of the peaky overflow traffic operated in Eq. (4). This leads to an overestimation of z and higher values of the blocking probability. An accurate evaluation of V^B_{OEO} would require the calculation of the parameters of the non-Poisson traffic A_{OEO}, which is anyway possible based on the Fredericks' theory [18]. By applying Lindberger's method [19] the blocking probability at the wavelength converters set is calculated, using Eq. (4) and Eq. (5), and results in

$$\Pi_{OEO} = \mathcal{B}\left(\frac{N_C}{z}, \frac{A_{OEO}}{z}\right) \quad (6)$$

Finally, the overall blocking probability of the system is

$$\Pi_{tot} = (1 - \mathcal{B}(N_W, N_W A_W))\, \Pi_{OEO} + \mathcal{B}(N_W, N_W A_W) \quad (7)$$

where $\mathcal{B}(N_W, N_W A_W)$ is the overflow probability on an output interface and represents the lower bound on blocking probability, corresponding to ideal OEO conversion with an infinite number of wavelength converters.

V. Numerical Results

This section presents numerical results aimed at offering design support for the dimensioning of OEO conversion resources available to the orchestrator.

The blocking probability of lightpath requests with wavelength conversion capability, calculated using Eq. (7), is represented in Fig. 3 and Fig. 4, as a function of the offered traffic per wavelength A_W, varying the number N_C of OEO wavelength converters and the number N_S of optical nodes in the network as parameters, respectively. In addition, both the worst case with no wavelength conversion and the lower bound with ideal wavelength conversion are represented.

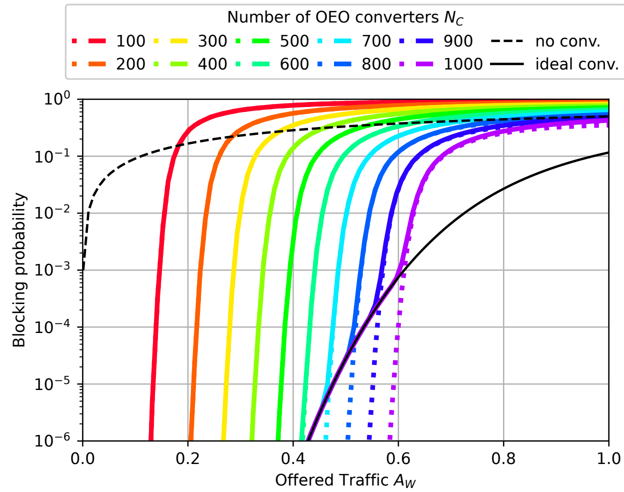

Fig. 3. Blocking probability as a function of the traffic per wavelength, varying the number N_C of OEO converters as a parameter, for $N_S = 10$, $N^S_I = 10$, $N_W = 40$. Black lines represent performance with no wavelength converters (dashed) and infinite wavelength converters (solid), respectively

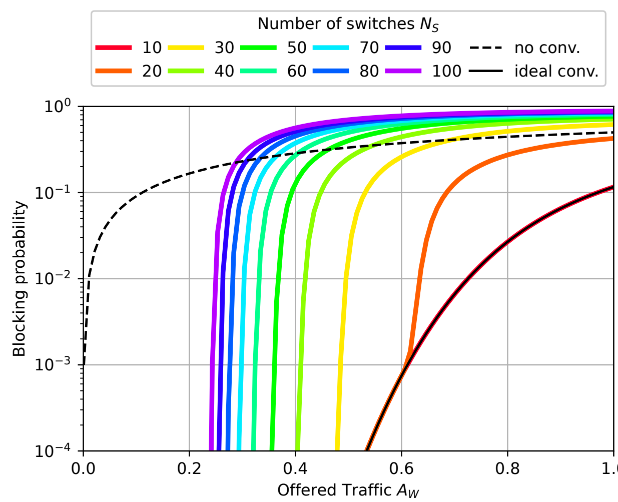

Fig. 4. Blocking probability as a function of the traffic per wavelength, varying the number of network nodes N_S as a parameter $N_C = 2000$, $N^S_I = 10$, $N_W = 40$. Point lines represent the contribution to blocking of the wavelength converters only. Black lines represent performance with no wavelength converters (dashed) and infinite wavelength converters (solid), respectively

In Fig. 3 the effect of the wavelength conversion is shown, as a function of the lightpath traffic per wavelength A_W, for $N_S = 10$, $N^S_I = 10$, and $N_W = 40$. By increasing the number N_C of OEO converters, blocking performance curves are shifted from the worst case to the best case. The worst case curve lies below the maximum of the other curves as a consequence of the approximation on the variance V^B_{OEO} that produce an upper bound of blocking performance in its turn, as mentioned above. In the same figure, the effect of the two contributions to loss considered in Eq. (7) is highlighted by plotting also the loss at the OEO converters in dotted lines, as calculated by Eq. (6). By increasing the number of OEO converters the curves move towards the best one so that the design can be optimal, e.g., to have a blocking probability $\Pi_{tot} < 10^{-3}$ with A_W up to 0.6, about $N_C = 1000$ wavelength converters are needed. It is worthwhile to remind that these wavelength converters are virtualized abstractions of wavelength converters sparse in the networks, whose reachability is ensured by the SDN network control.

In Fig. 3 the impact of network size in terms of the number of nodes is represented assuming that 2000 wavelength converters are available for nodes with $N_I^S = 10$ and $N_W = 40$. Blocking performance requirements put a limit on network size, providing that enough OEO converters are available for wavelength contention resolution. With $N_C = 2000$, a maximum network size $N_S = 20$ is allowed to have $\Pi_{tot} < 10^{-3}$ with $A_W <= 0.6$.

VI. Conclusions

In this paper, the impact of lightpath setup on the orchestration of resources SDN-empowered disaggregated optical networks is assessed, and related to end-to-end service provisioning using a layered functional model.

A traffic model is introduced to investigate the correlation between the availability of (abstracted) resources and the fulfilment of service requirement, with a focus on service request blocking probability, i.e., the ability of the orchestration system to accept and successfully carry out demands for end-to-end lightpath allocation.

The results show that request blocking in a typically acceptable range is achievable for the considered amount of network nodes and OEO conversion resources. Furthermore, they hint at the individual contributions that the aforementioned amounts give to the overall blocking behavior.

The proposed analysis can be further extended by considering also latency requirements for end-to-end service and additional parameters to characterize the abstracted resources, such as those related to the reachability aspects that consider abstracted resource location in addition to their availability and quality of service parameters.

Acknowledgments

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