How to Enhance the Efficiency of Loss-Less Optical Burst Switching Networks with the Streamline Effect

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Abstract. *With the ongoing steady traffic increase in the Internet, the wavelength usage of the supporting optical networks is a critical network efficiency parameter. Therefore, this paper suggests a way how to efficiently and economically achieve this goal in the context of optical burst switching, a very promising technology that has been proposed to overcome the shortcomings of conventional WDM deployment, such as lack of fine bandwidth granularity in wavelength routing and electronic speed bottlenecks in the presence of bursty traffic. In order to mitigate the burst loss and achieve high network efficiency we adapt the loss-less paradigm defined by Coutelen et al. (2010), i.e., the CAROBS framework. In classical OBS networks, the streamline effect ensures a very low level of contention, i.e., efficient transmission, hence we define a routing guided only by the streamline effect. The resulting routing problem is formulated as an optimization model which is solved using a decomposition technique to increase the scalability of the solution process.*

Keywords

Column-generation, loss-less, optical burst switching, optimizations.

1. Introduction

In recent years, servers in data centers providing multimedia content were the main drivers of rapid increase of consumed bandwidth in the Internet [1]. The bandwidth demand was predicted to culminate around year 2012; however, the exponential increase of required bandwidth prevails. The sources of this bandwidth requirement increase are no longer computers and smart devices, but the applications that run on smart devices [1]. This trend accelerates the need for fast and reliable switching technology to support this new traffic. The current approach where operators upgrade their line-cards and routers is no longer sustainable because all these routers consume a considerable amount of energy and are very close to their technological limits [1],[2].

Therefore, the switching concept called *bypass* was introduced. Bypass is used in optical networks to allow switching a light beam between any two ports of an optical cross connect (OXC) without electronic processing. Based on this principle, the three main all-optical paradigms emerged: optical circuit switching (OCS), optical packet switching (OPS), and optical burst switching (OBS). OCS usually comes with an overlay technology such as optical transport hierarchy (OTH) in order to achieve a higher efficiency of used wavelengths. OCS cannot ensure a wavelength efficiency higher than 40 % [3]. Therefore, OPS and OBS were defined to refine wavelength capacity with sub-wavelength scheduling – all-optical grooming. OPS relies on very fast switching technology that is not yet ready for production deployment thus OPS is not feasible in the near future. On the other hand, OBS concatenates some packets into one burst which is longer hence the switching is less frequent, and viable with current technology. However, the perennial weakness of the OBS is the network congestion and contention leading to burst losses [4]. Burst loss has been intensively studied [5], as well as loss-less architectures [6]. Later, the bypass was combined with fine spectrum allocation which originates in wireless networks, i.e. orthogonal frequency-division multiplexing (OFDM), and due to the improvement of optical technologies the optical OFDM (OOFDM) could be introduced. This article is not focused on OOFDM because the OOFDM transceivers rely on very comprehensive digital signal processors dealing with clock synchronization. However, our motivation is to show performance for systems with granularity of one wavelength, and the efficiency of these systems can be further extended by more advance techniques on the physical layer in future work.

Currently, our focus is the wavelength efficiency of the OBS loss-less architecture proposed by Coutelen et al., the CAROBS framework [6]. The CAROBS framework ensures higher wavelength efficiency than regular OBS [4], [6]. Therefore, in this study, we adapt this framework in order to enhance the routing and the provisioning for all-optical networks. We aim to increase as much as possible the wavelength usage while preserving the loss-less requirements in terms of flow merging. Note that any bandwidth requirement increase implies an increase of OPEX and CAPEX: we must use the optical medium as efficiently as possible to reduce expenses [7].

This paper is organized as follows. In Section 2. , we review the recent OBS and streamline effect (SLE) [8] studies. In Section 3. , we briefly recall the CAROBS framework. We then propose the RWA-SLE (Routing and Wavelength Assignment - Streamline Effect) model in Section 4. , a new routing and provisioning scheme only governed by the steam-line effect. Numerical and simulation results are presented in Section 5. .

2. Related Works

The prime motivation of all-optical frameworks, including OBS, is to reduce delivery times, increase network throughput, and reduce CAPEX and OPEX [7]. All-optical frameworks use optical bypass technology thanks to OXCs. OBS uses both OXCs and sub-wavelength scheduling, so burst contentions causing performance decrease might occur, even with optimized routing. Therefore, some recent studies redesign OBS architectures using time slots [9]. Other studies returned to the principals of all-optical networks using wavelength routing for bursts [10]. In most cases, however, these architectures rely on a ring topology which is either less scalable, or less efficient from the perspective of wavelength utilization compared to dynamic just-in time signaling used in OBS and OPS [9] networks.

Pavon-Marin et al. [11] carried out an in-depth analysis of buffer-less OBS architectures, and concluded that buffer-less OBS architectures are not viable for mesh topologies. According to their conclusion [11], the limiting factors of OBS are the inter-burst gap, a separate control wavelength, and contention resolution using burst drop approach. In other words, only the optical contention resolution process can be changed otherwise we are changing the OBS paradigm itself. Therefore, buffering seems to be the only way to increase OBS network performance. Unfortunately, very little work has been done on buffering in OBS networks.

Only a few early concepts use fiber delay lines (FDL) [12]. Deployment of lengthy fibers, however, is problematic on most premises, and purely optical random access memories are not still ready for production deployment. Consequently, some authors investigated scenarios using electrical memories [6], [13]. Among these works [6], [13] there is the CAROBS framework proposed by Coutelen et al. [6]. Coutelen et al. published a series of papers dealing with node architecture and its performance, but the authors did not devote any attention to the dimensioning and to network performance.

Contention does not cause loss in loss-less OBS networks, but increases the end-to-end delay because the contending bursts are stored in a memory. Therefore, it is beneficial to minimize the number of situations where contention can occur – flow merging [8], [14]. Flow merging is a situation when multiple flows from different ingress ports are switched towards to the same egress port, and the flow merging occurs only for flows at the same wavelength. The approach minimizing merging is widely recognized as SLE [8], and was studied for classical OBS. Consequently Barradas et al. came up with an analysis of burst loss probability (BLP) for routing maximizing SLE [14]. The conclusion is that when wavelength conversion (WC) is used the routing maximizing SLE performs better then the routing only based on shortest-paths. As long as CAROBS allows WC thanks to the electrical buffering the routing maximizing SLE is worth it. However, as we showed in [15] some buffering always prevail because of secondary contention [15]. The secondary contention is an unique situation caused by buffering due to the un-buffered bursts can content with bursts approaching the node. In this paper we focus on routing allowing only SLE.

3. CAROBS Description

The objective of the CAROBS framework is to provide all-optical features without any burst loss. In order to meet this goal, the architecture of the Core and Edge nodes are merged into one CAROBS node in the CAROBS framework, see Fig. 1. Due to this architectural change, and to the transmission mechanism called burst trains, the CAROBS framework can ensure the all-optical grooming. Every burst train contains a few bursts, which are called cars in the CAROBS notation.

Bursts are destined to nodes along the same flow-path [6]. Every burst train is signaled by one Header containing a general information section, and car sections that provide information about particular bursts of the burst train [6]. Each car is separated from the following car by time that is equal to the time necessary for OXC reconfiguration – d_s. The CAROBS framework uses JET (just enough time) [4] to signal flow-path for burst train. Each car can ensure transmission of packet/frame oriented traffic featured in TCP/IP, Ethernet, ATM, etc. Additionally, each car contains aggregated data for only one destination edge node (edge refers to the topological location). In a series of articles, Coutelen et al. showed higher performance of CAROBS framework against the classical OBS [4], [6]. However, he did not work on the routing and provisioning schemes for CAROBS networks. The increase of performance is our motivation to work further with CAROBS framework and show the optimal way of using the CAROBS framework to design an all-optical network.

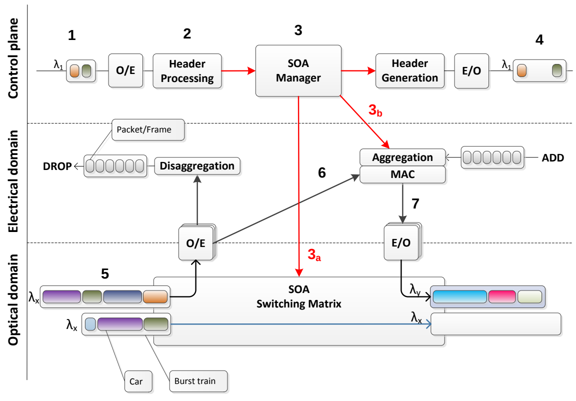


Fig. 1: CAROBS node resolves burst contention with recourse to an electrical buffer. The contenting burst train is sent to MAC layer and stored until the output direction is available. The CAROBS header of the contenting burst is also modified as a result of buffering delay [6].

The CAROBS node architecture defined by CAROBS framework is depicted in Fig. 1. The horizontal lines represent the input and output ports. Additionally, we labeled the ports by λ symbol. λ_1 represents the dedicated wavelength for the control channel, and λ_x represents one of the wavelengths used for optical transmission. The CAROBS node architecture spans three logical layers, as illustrated in Fig. 1. The control plane is on the very top. The control plain contains the *SOA Manager* reading CAROBS headers and determining further node actions. According to the CAROBS header's content the CAROBS node can *(i)* switch a whole burst train, *(ii)* groom-out the first car and switch the rest of the burst train, *(iii)* buffer contenting cars on the electrical memory. To do so, the SOA Manager creates a set of instructions for the SOA Switching Matrix (MX), and forwards the CAROBS header to the next CAROBS node on the dedicated wavelength – λ_1. The middle layer is called electrical domain. The name was chosen accordingly because of only electronic processing on this layer. Electrical domain is used for *(i)* aggregation, disaggregation user traffic, *(ii)* buffering of contenting burst trains in the Media Access Control (MAC) block. The bottom layer strictly resides in optical domain. This layer is strictly analogue, and represents the physical layer where all cars are switched. It contains the MX ensuring switching of the optical signal, and for the switching the semiconductor optical amplifier (SOA) is used due to its fast switching speed. If contention occurs, the contenting burst trains are switched to the dedicated port for electrical buffering. These ports are directly connected to the O/E blocks, which convert the optical signal to the electrical domain. The contenting bursts are sent to the MAC where they are converted from optical to electrical domain.

4. Streamline Effect Based Routing

Our goal, when designing the CAROBS network under SLE assumption [8] is to support as much traffic as possible while using the smallest possible number of wavelengths. We formulate the routing and provisioning using a mathematical model, called SLE-RWA.

The SLE is observation that bursts travelling in a common link are streamlined and do not contend with each other until they diverge [8]. Consequently, in order to avoid contention, the idea is to allow the merging of two flows at a node v if v is the source node of one of the two flows. This way, it is always possible to avoid contention by delaying, in the electronic domain, the launch of the bursts of the flow originated at v until the merging is free of contention. Resulting flows (paths) will be called SLE compliant paths in the sequel.

In view of being able to design a scalable solution process for the SLE-RWA model, we propose a formulation that can be solved using decomposition techniques. The SLE-RWA model amounts to select the best routing and provisioning configurations out a huge set of potential configurations. Each configuration is defined by a set of provisioned flow-paths, which are all using the same wavelength, and the wavelength continuity is enforced. Each configuration contains SLE compliant paths, and fraction of D_{sd} traffic on each $\{v_s, v_d\}$ flow, i.e., the amount of provisioned traffic in this configuration. The configuration decomposition scheme is depicted in Fig. 2.

Parameters of the SLE-RWA model are defined below: $\mathcal{SD}$ = set of node pairs such that $D_{sd} > 0$
C = set of wavelength configurations, indexed by c

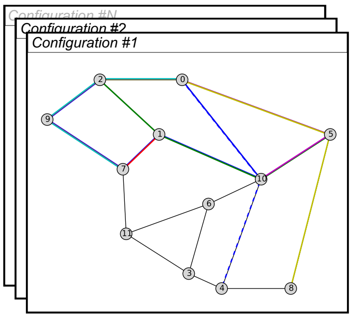


Fig. 2: An example of a configuration set containing N wavelength configurations. Each configuration only contains compliant SLE paths which are captured by different colours in the figure.

c = generic wavelength configuration: it is characterized by a set of paths p^c that are SLE compliant. Each path is characterized by:

- d^c_{sd} = amount of bandwidth routed in c for $\{v_s, v_d\} \in \mathcal{SD}$,
- $a^c_{sd} = 1$ if a $\{v_s, v_d\} \in \mathcal{SD}$ flow is supported by configuration c.

There are two sets of variables:
$(z_c)_{c \in C}$ where z_c is an integer, non-negative variable specifying the number of wavelengths for which the configuration c is selected.
U_{sd} = amount of un-provisioned traffic for $v_s, v_s \in \mathcal{SD}$.

The objective function of the SLE-RWA model minimizes the amount of un-provisioned traffic U_{sd}, while using a minimum number of flows. It can be written is as follows:

$$\min \sum_{\{v_s,v_d\} \in \mathcal{SD}} U_{sd} + \sum_{c \in C} z_c \left(1 + \sum_{\{v_s,v_d\} \in \mathcal{SD}} a^c_{sd} \right), \quad (1)$$

subject to:

$$\sum_{c \in C} z_c \leq W, \quad (2)$$

$$\sum_{c \in C} d^c_{sd} z_c \geq D_{sd} - U_{sd} \qquad \{v_s, v_d\} \in \mathcal{SD}, \quad (3)$$

$$z_c \in \mathbb{Z}^+ \qquad c \in C. \quad (4)$$

Selected configurations ensure enough capacity in the network to support the traffic $D_{sd} - U_{sd}$ for every $\{v_s, v_d\} \in \mathcal{SD}$ combination Eq. (3). Thanks to constraints Eq. (2), we do not exceed the number of available wavelengths.

4.1. SLE-RWA Solution

In order to solve the SLE-RWA model Eq. (1), Eq. (2), Eq. (3), Eq. (4), we use a column generation method [16]. We, therefore, start by a Restricted Master Problem (RMP), i.e., Eq. (1), Eq. (2), Eq. (3), Eq. (4) with an initial set of configurations. To keep the initialization simple, initially generated configurations only support one flow each. The current RMP is next enriched with augmented configurations, i.e., configurations which, when added to the RMP, improve the value of its linear relaxation value. In order to do so, we need a configuration generator, this is the so-called pricing problem in the framework of the column generation method. The RMP and the pricing problem (PP) are then alternatively solved until the optimality condition (to guarantee that we have reached the optimal solution of the linear relaxation) is satisfied. The flowchart capturing the iterative process is depicted in Fig. 3.

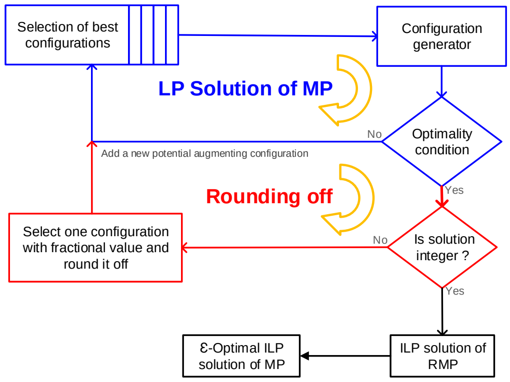


Fig. 3: Flowchart of the solution process: column generation and rounding off framework.

A configuration is only added to the set of configurations if it is an improving one, which means that the value of PP objective function (i.e., the reduced cost, denoted by $\overline{\text{COST}}$) is negative (see [16] if not familiar with linear programming concepts). If the reduced cost is positive, we have reached the optimal value $z^\star_{\text{LP}}$ of the linear relaxation of Eq. (1), Eq. (2), Eq. (3), Eq. (4), and then the *LP Solution of MP* stops. The focus shifts to the derivation of integer values for the z_c variables.

Consequently, we next solve the RMP as an ILP program, however, the ILP solution of RMP only selects from the set of configurations that have been generated for reaching the optimal LP solution of RMP, so the integer value of the objective function is not necessarily minimal. We decided to use a *rounding off* approach to solve the ILP RMP. Such an approach iteratively selects integer values for one or a subset of variables z_c and then if necessary, generates additional configurations until reaching again an optimal LP solution taking into account the fixed variables, and the remaining free continuous variables. Subsequently, in practice, it allows reaching an integer solution that can be very close to the optimal integer value, or at least an integer value $\tilde{z}_{\text{ILP}}$ for which we can estimate the accuracy (denoted by $\varepsilon = (\tilde{z}_{\text{ILP}} - z^\star_{\text{LP}})/z^\star_{\text{LP}}$).

4.2. Configuration Generator

The *configuration generator* is very important because it generates SLE compliant improving configurations through communication with the RMP [16]. Each path in the network is calculated using flow constraints. We define the following set of variables. (c index is omitted to alleviate the presentation of the pricing problem).

b_{sd} = amount of routed bandwidth in the configuration from node v_s to v_d,
$\varphi_\ell^{sd} \in \mathbb{R}^+$: Amount of provisioned bandwidth in the configuration from v_s to v_d on link ℓ,
y_ℓ^{sd} : Decision variable such that $y_{sd}^\ell = 1$ if some traffic from v_s to v_d is provisioned on link ℓ in the configuration,
$y_{\ell_i \ell_o}$: Decision variable indicating that $\{v_s, v_d\} \in \mathcal{SD}$ flow is routed from ℓ_i to ℓ_o at node $v = \textsc{src}(\ell_o)$.

The objective function of the pricing problem, i.e., the configuration generator, is defined as follows by the reduced cost:

$$\overline{\text{COST}} = 1 + \sum_{\{v_s,v_d\}\in\mathcal{SD}} a_{sd} - u^{Eq.\ (2)} - \sum_{\{v_s,v_d\}\in\mathcal{SD}} u_{sd}^{Eq.\ (3)}\, b_{sd}, \quad (5)$$

where $u_{sd}^{Eq.\ (3)}$ and $u^{Eq.\ (2)}$ are the dual variables associated with Eq. (3) and Eq. (2), respectively. The set of constraints is as follows:

$$\sum_{\ell\in\omega^+(v)} \varphi_\ell^{sd} - \sum_{\ell\in\omega^-(v)} \varphi_\ell^{sd} = \begin{cases} b_{sd} & \text{if } v = v_s \\ -b_{sd} & \text{if } v = v_d \\ 0 & \text{otherwise} \end{cases} \quad (6)$$
$$v \in V, \{v_s, v_d\} \in \mathcal{SD},$$

$$\sum_{(v_s,v_d)\in\mathcal{SD}} \varphi_\ell^{sd} \le B \qquad \ell \in L, \quad (7)$$

$$\varphi_\ell^{sd} \le D_{sd}\, y_\ell^{sd} \qquad \ell \in L, \{v_s, v_d\} \in \mathcal{SD}, \quad (8)$$

$$y_\ell^{sd} < \varphi_\ell^{sd} + 1 \qquad \ell \in L, \{v_s, v_d\} \in \mathcal{SD}, \quad (9)$$

$$\sum_{\ell\in\omega^+(v_s)} y_\ell^{sd} \le a_{sd} \qquad (v_s, v_d) \in \mathcal{SD}, \quad (10)$$

$$y_{\ell_i}^{sd} + y_{\ell_o}^{sd} - 1 \le y_{\ell_i\ell_o} \qquad \ell_i, \ell_o \in L : \textsc{dst}(\ell_i) = \textsc{src}(\ell_o) = \{v\},$$
$$v \in V, (v_s, v_d) \in \mathcal{SD} : v \notin \{v_s, v_d\}, \quad (11)$$

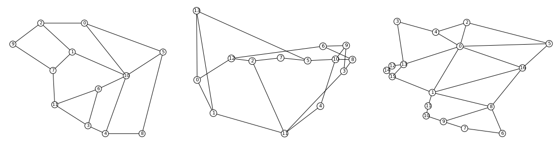
$$\sum_{\ell_i\in L:\textsc{dst}(\ell_i)=\textsc{src}(\ell_o)} y_{\ell_i\ell_o} \le 1 \qquad \ell_o \in L, \quad (12)$$

$$y_\ell^{sd} \in \{0,1\}, \varphi_\ell^{sd} \ge 0 \qquad \ell \in L, \{s, d\} \in \mathcal{SD}, \quad (13)$$

$$d_{sd} \ge 0 \qquad \{s, d\} \in \mathcal{SD}, \quad (14)$$

$$y_{\ell_i\ell_o} \in \{0,1\} \qquad \ell_i, \ell_o \in L : \textsc{dst}(\ell_i) = \textsc{src}(\ell_o). \quad (15)$$

Constraints Eq. (6), also called flow constraints, allow computing the amount of bandwidth that can be routed from v_s to v_d in the configuration under construction; subsequently, these constraints allow finding a path through the given network. The resulting flow-path is not necessarily the shortest one, and does not use full capacity of each link $\ell \in L$ because we allow grooming. This means more flows can use the same link ℓ. In other words, one traffic request D_{sd} can be routed on multiple wavelengths, i.e., different links. However, the capacity of each link can not be exceeded, hence the constraints Eq. (7). Flow variables are nonnegative continuous variables as they determine the amount of provisioned bandwidth. The remaining constraints, however, are based on binary variables y_ℓ^{sd}, in order to identify the links used by the various flows, with respect to their source and destination. We define constraints Eq. (8), Eq. (9) to compute the values of the y_ℓ^{sd} variables, which will be used to determine SLE compliance. Constraints Eq. (10) are used to indicate existence of at least one flow from v_s to v_d in the configuration under construction. The values of a_{sd} will be next used in the RMP objective function to minimize the number of flows in the network.



(a) Polska (b) Nobel-US (c) Germany

Fig. 4: Selected topologies for the experiments [17].

At last but not least, the pricing problem contains constraints enforcing SLE compliance in the configuration under construction. We use two set of constraints Eq. (11) and Eq. (12) where constraints Eq. (11) only generate the temporary OXC configuration, i.e., switching connection matrix, by generating the variables $y_{\ell_i\ell_o}$. Variable $y_{\ell_i\ell_o}$ is equal to 1 only if there is a flow routed from link ℓ_i to link ℓ_o. These constraints take into account already streamlined flows coming from input link ℓ_i. Constraints Eq. (11) translate the following constraints:

$$y_{\ell_i\ell_o} = \max_{(v_s,v_d)\in\mathcal{SD}:v\notin\{v_s,v_d\}} y_{\ell_i}^{sd}\, y_{\ell_0}^{sd}$$
$$v \in V\ ;\ \ell_i, \ell_o \in L : \ell_i \cap \ell_o = \{v\}, \quad (16)$$

which express that if there is at least one flow routed from ℓ_i to ℓ_o then $y_{\ell_i\ell_o} = 1$. Subsequently, constraints Eq. (12) enumerate the number of flows routed to output link ℓ_o of node $v = \textsc{src}(\ell_o)$. By setting the upper limit to be one, we actually prevent any merging, which means we only allow aggregation at node $v = \textsc{src}(\ell_o)$. In other words, we enforce path SLE compliance in the network. The remaining constraints take care of the domains of the variables.

5. Numerical Experiments and Simulation

5.1. SLE-RWA Routing and Provisioning

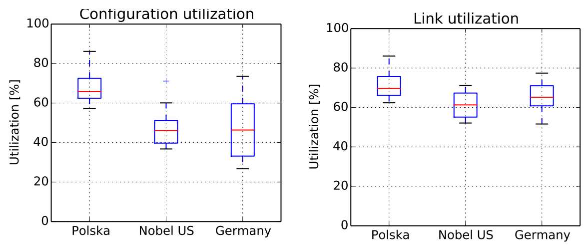
The SLE-RWA routing and provisioning algorithm provides enough information necessary for traffic routing with no merging flows, but still with some contentions caused by the aggregation. The impact of aggregation on contention (secondary contention) can be only verified by a time domain analysis – simulation. In our analysis, we use the CAROBS framework [18] that we previously implemented within the OMNeT++ simulator. The traffic performance parameters we look at are the burst buffering probability (BBP), access delay (ACC) which informs how much of time is necessary in order to wait prior the output wavelength and port is again ready for another burst train sending, buffering delay (BD) which provides information for how long each burst train is stored in the electrical memory, and end to end delay (E2E) which does not contain propagation delay because our focus is to show the system performance. The BBP shows how much of the traffic undergoes buffering. Subsequently, the BD shows how much delay each buffered burst train gains. Although the buffering can be seen as beneficial because it prevents burst losses, the buffering delay can be high. The total impact of buffering can be noticed on E2E as a main quantifying parameter of CAROBS viability.

In order to verify the CAROBS network performance, we ran tests on three network topologies depicted in Fig. 4. These topologies are used often by other researches and come from 17 [17]; however, since the traffic D_{sd} provided by SDNlib was not sufficient for the purpose of our experiments, we generated D_{sd} randomly using uniform distribution.

We used both the topological and traffic information of the SLE-RWA model in order to obtain traffic routing. Based on the routing we carry out 20 simulations to mitigate impact of random number generator seed used in the simulator for traffic generation. The source nodes s supply traffic generated according to a Poisson distribution to the CAROBS network in the simulation. The source nodes generate payload packets with constant size (100 kb). Then, these packets create flows to supply aggregation queues to generate bursts. JET is used as a signaling protocol and LAUC-VF algorithm [19] for burst assembly. The data rate of each wavelength is 10 Gbps.

5.2. Analysis of the Resource Usage

The routing performance and traffic performance parameters for the three topologies of CAROBS networks are captured in Tab. 1. The values of traffic performance parameters are calculated as a mean value over all nodes in the network where these traffic performance parameters are measured. We do not provide confidence intervals of these values because the values of Standard error are negligible compared to the mean values.



(a) Configuration utilization – indicates overall utilization of configurations including even not used links

(b) Link utilization – indicates utilization of links that support some traffic flows

Fig. 5: Resource usage depicted using box plots.

The routing performance parameters disclose very interesting property of CAROBS networks: very high maximal configuration utilization. The routing performance parameters are focused on the link and configuration, i.e., wavelength, utilization. The link utilization is calculated using Eq. (17), and the average link utilization is based on $U_\ell > 0$.

$$U_\ell = \frac{\sum\limits_{(v_s,v_d)\in\mathcal{SD}} \varphi_\ell^{sd}}{B} \qquad \ell \in L, \tag{17}$$

where this formulation applies to a specific configuration.

On the other hand, the configuration utilization includes links which do not support any flow, i.e., $U_\ell = 0$. Therefore, the configuration utilization is calculated using Eq. (19).

$$U_c^L = \left\{ \sum_{(v_s,v_d)\in\mathcal{SD}} \varphi_\ell^{sd} \quad | \quad \ell \in L \right\} \qquad c \in C, \tag{18}$$

$$\text{Avg. configuration utilization} = \frac{\sum\limits_{c\in C}\sum\limits_{\ell\in L} U_{c,\ell}^L . z_c}{B.|L|.\sum\limits_{c\in C} z_c}. \tag{19}$$

Tab. 1: The performance parameters obtained from SLE-RWA algorithm and OMNeT++ simulations which verified the routing, and allowed the traffic performance parameters enumeration.

Topology		**Polska**	**Nobel US**	**Germany**
Nodes	[-]	12	14	17
Links	[-]	18	21	26
Diameter	[-]	4	3	6
Routing performance parameters				
Number of wavelengths	[-]	7	9	16
Max. configuration utilization	[%]	86.12	71.12	73.52
Avg. configuration utilization	[%]	68.43	48.49	48.27
Avg. link utilization	[%]	71.68	61.90	65.50
Requested traffic	[Tbps]	1.33	2.18	5.02
Number of flows	[-]	121	182	272
Traffic performance parameters				
Burst buffering probability	[-]	0.242	0.069	0.068
Access delay	[ms]	0.022	0.025	0.049
Buffering delay	[ms]	0.257	0.211	0.252
End-to-end delay	[ms]	0.642	0.329	0.368

Tab. 2: Quantification of link-disjoint routing realizing RWA of an OCS network for the selected networks.

Topology		**Polska**	**Nobel US**	**Germany**
Number of wavelengths	[-]	12	13	23
Max. configuration utilization	[%]	72.86	71.15	77.11
Avg. configuration utilization	[%]	35.97	36.24	36.47
Avg. link utilization	[%]	35.97	36.24	51.07
Number of flows	[-]	144	209	322

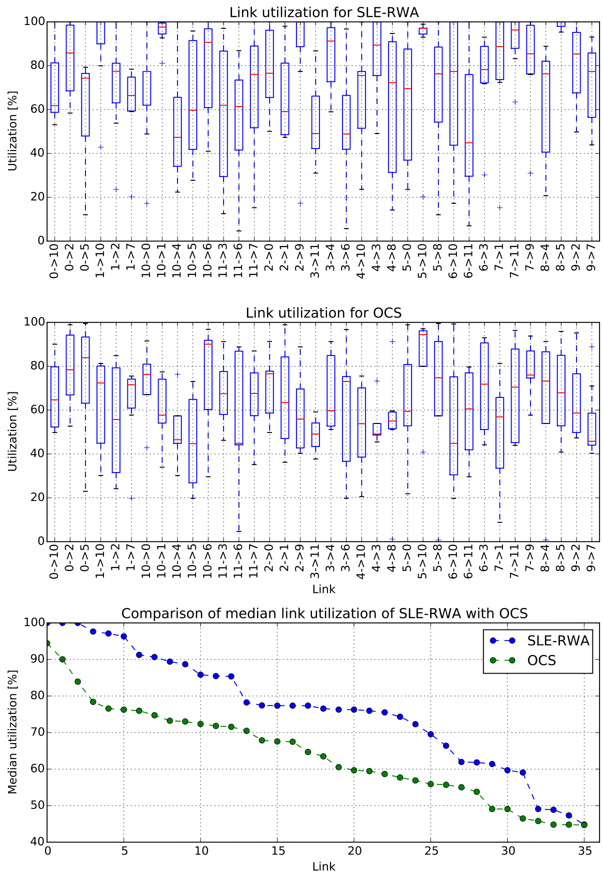


Fig. 6: This figure captures distribution of link utilization for each link across all used configurations for Polska newtwork topology and provides comparison to OCS.

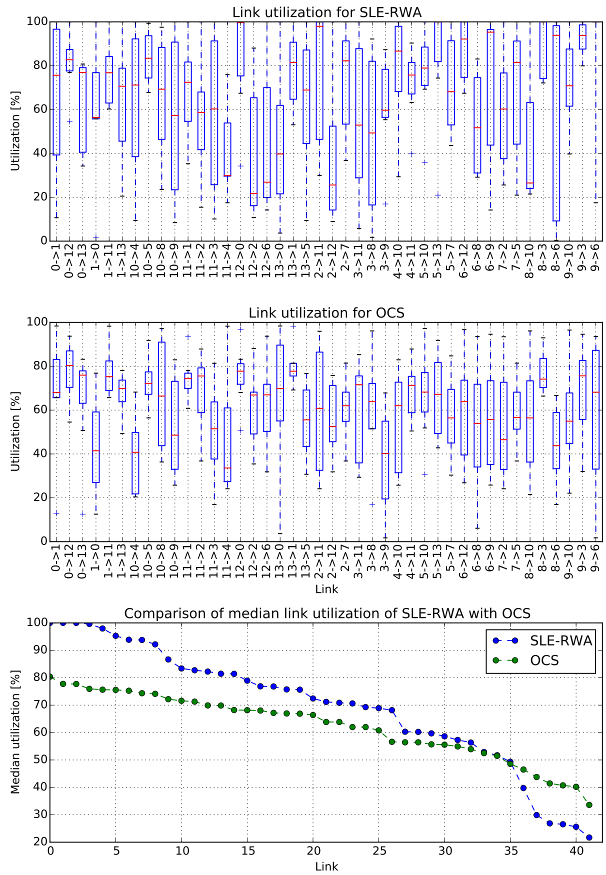


Fig. 7: This figure captures distribution of link utilization for each link across all used configurations for Nobel US newtwork topology and provides comparison to OCS.

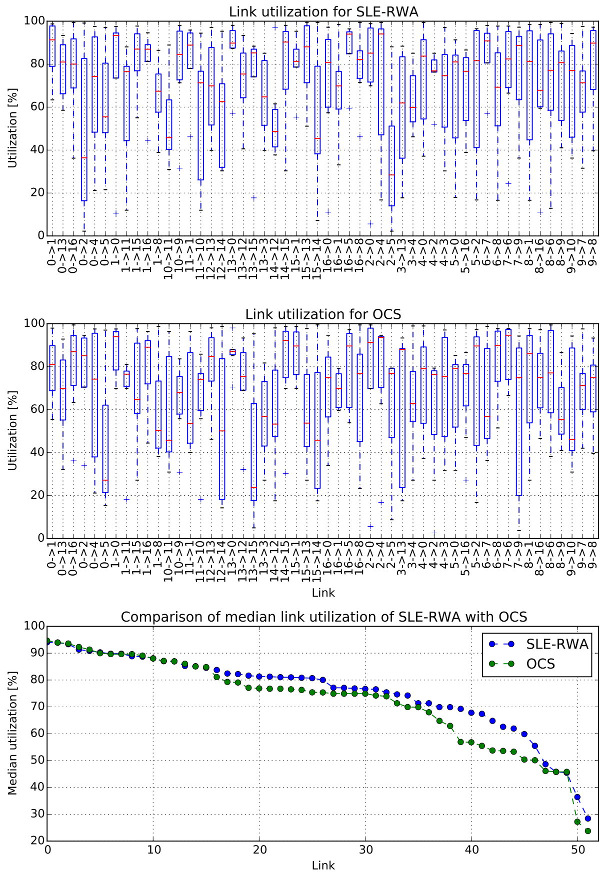


Fig. 8: This figure captures distribution of link utilization for each link across all used configurations for Germany newtwork topology and provides comparison to OCS.

The maximal configuration utilization is higher than 70 % which is significantly higher than what is possible to achieve in OCS networks that are based on link-disjoint traffic property [3]. In order to compare with OCS, a RWA [20] algorithm was implemented and evaluated in CPLEX. The results for link-disjoint RWA are captured in Tab. 2, and one can see that the average configuration utilization is about half and twice the number of wavelengths. The difference between maximal and average configuration utilization for SLE-RWA is relatively high for all studied cases as one can see in Fig. 5. This is partly explained by the detailed configuration and link utilization, on a link basis, in Fig. 6, Fig. 7, and Fig. 8, for each network topology. Therein, we can observe that some links belong to more routes than other, because of their location in the network and of the network connectivity. Consequently, the link bandwidth usage varies from one link to the other.

Furthermore, we can observe that a minimum number of configurations are deployed for a considerable amount of traffic from Fig. 5(a). This observation leads to the question of how efficiently the traffic is distributed (load balancing) using a pure SLE-RWA routing and provisioning scheme. We then evaluated the efficiency of links that are supporting some traffic Fig. 5(b). Here we can see that the average link utilization of used links is considerably higher than the average configuration utilization. Also, the variance of link utilization is significantly smaller that is caused by considering only used links.

Very high link utilization is potentially dangerous because of the secondary contention, and buffering as sequel. The secondary contention in CAROBS network is caused by a) aggregating traffic b) rescheduled traffic that was buffered because of a). The studied networks, however, show low values of buffering delay. Nevertheless, based on the values of E2E delay, we can say that burst trains are buffered up to 3 times on average in the Polska network, and 2 times for the two other networks on their way from source to destination. Further reduction could be achieved by adding extra constraint limiting the number of buffering operations along the lightpaths. However, there exists a compromise between limiting the number of buffering operations, and configuration efficiency in terms of resource usage. Moreover, more wavelengths may be necessary if we restrict too much the number of buffering operations.

6. Conclusions

This paper focused on the CAROBS network efficiency through the design of a scalable routing algorithm aiming at exploiting SLE, so only the extreme values of performance parameters are presented. A decomposition formulation and solution scheme was used in order to find maximal levels of configuration resource utilizations. The configuration utilization translates to wavelength efficiency in real networks hence it is very important to achieve high values because of CAPEX and OPEX savings. The proposed SLE-RWA model indicates that the maximal achievable configuration utilization is higher than 70 % for studied network topologies. This high wavelength utilization is achieved thanks to the grooming on the optical layer, and buffering that provides the CAROBS framework.

Buffering in CAROBS networks, however, means an increase of the E2E delay, for the buffered burst trains are stored in electronic memory for some time. Based on the values in our analysis, we can see that the BD is manageable and means negligible impact system delays. The E2E can be reduced by limiting the number of buffering along the flow-paths. Nevertheless, the current values, without the buffering limit, are very reasonable for a network with a link utilization around 70 % and more.

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