On the Highly Stable Performance of Loss-Free Optical Burst Switching Networks

Milos KOZAK[1], *Brigitte JAUMARD*[2], *Leos BOHAC*[1]

[1]Department of Telecommunication Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague, Technicka 2, 16000 Prague, Czech Republic
[2]Department of Computer Science & Software Engineering, Faculty of Engineering and Computer Science, Concordia University, 1515 Rue Sainte-Catherine, H3G 2W1 Montreal, Canada

milos.kozak@fel.cvut.cz, bjaumard@cse.concordia.ca, bohac@fel.cvut.cz

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Abstract. *Increase of bandwidth demand in data networks, driven by the continuous growth of the Internet and the increase of bandwidth greedy applications, raise the issue of how to support all the bandwidth requirements in the near future. Three optical switching paradigms have been defined and are being investigated: Optical Circuit Switching (OCS); Optical Packet Switching (OPS); and Optical Burst Switching (OBS). Among these paradigms, OBS is seen as the most appropriate solution today.*

However, OBS suffers from high burst loss as a result of contention in the bufferless mode of operation. This issue was investigated by Coutelen et al., 2009 who proposed the loss-free CAROBS framework whereby signal convertors of the optical signal to the electrical domain ensure electrical buffering. Convertors increase the network price which must be minimized to reduce the installation and operating costs of the CAROBS framework. An analysis capturing convertor requirements, with respect to the number of merging flows and CAROBS node offered load, was carried out. We demonstrated the convertor location significance, which led to an additional investigation of the shared wavelength convertors scenario. Shared wavelength convertors significantly decrease the number of required convertors and show great promise for CAROBS. Based on this study we can design a CAROBS network to contain a combination of simple and complex nodes that include none or some convertors respectively, a vital feature of network throughput efficiency and cost.

Keywords

CAROBS, hypothesis testing, merging flows, Optical Burst Switching, routing, stationary signal.

1. Introduction

Not as long ago, twisted pairs were replaced by optical fibers in order to ensure higher bandwidth and reach greater distances. Further, Wavelength Division Multiplex (WDM) currently uses already deployed fibers more efficiently supporting wavelengths at 100 Gbps. However, network node power consumption increases as wavelength bandwidth increases which is the result of the switching paradigm residing in the electrical domain using electronic cross-connects [1] where the optical signal must be converted to the electrical domain to be routed. This approach is recognized as the point-to-point network topology relying on Optical-Electrical-Optical (OEO) conversion. The OEO conversion allows reaching long distances and designing mesh topologies but the network performance is limited as it does not allow groom different optical signals [1], which is necessary to decrease operational cost. Therefore, a new strategy incorporating all-optical bypass started to be used as the way of decreasing network operational cost [1] and [2]. This strategy opened a new area of optical networking: All-optical networks.

All-optical networks can be realized with different switching granularities. Optical Circuit Switching (OCS), which is currently deployed as a part of SDH/Sonet and IP over WDM networks, is characterized by switching at the level of wavelengths, with lightpaths usually being long-term settings. OCS paradigm uses bypass nodes, however, grooming is carried out electronically. On the other side of the spectrum, Optical Packet Switching (OPS) allows all-optical grooming while providing sub-wavelength switching of small packets. However, OPS relies on fast switching cross-connects that are not affordable for production (at least as for today). In a nutshell, Optical Burst Switching provides sub-wavelength granularity in the optical domain thanks to so-called bursts where a burst is defined as a set of continuous packets destined to a common egress point, so that the optical cross-connect does not need to change frequently or quickly. OBS allows very fast switching without any burst OEO, and only the burst control message [3] undergoes OEO. OBS is a promising and mature technology that is currently being tested by some ISPs in the field [4], [5] and [6].

However, the perennial always mentioned weakness of OBS is the high burst loss caused by the combination of burst contention and congestion: when burst contention occurs, only one burst is switched, others are dropped, and the dropped bursts are sentenced by the burst priorities or arrival times. Various concepts minimizing burst loss have emerged, with various approaches for resolving contention, e.g., various routing strategies [7] and [8], wavelength conversion [10] and time-slots [10] and [11], as well as some zero burst loss concepts with the addition of electrical buffering [12] and [13], or for particular topologies [13]. The CAROBS framework proposed by Coutelen et al. [13] underpins these concepts, combines Core and Edge node architectures, brings all optical grooming, allows wavelength conversion with recourse to OEO conversion, and uses electrical buffering to provide a loss-free mode of operation. From our perspective, the CAROBS framework is very promising framework for future deployments of asynchronous OBS networks.

The motivation of this paper is to evaluate the viability of CAROBS in terms of CAPEX, OPEX and performance parameters. We carry out comprehensive set of simulations in order to enumerate the number of optical to electrical (O/E) conversion blocks that are essential for loss-free paradigm, but the O/E blocks are recognized as the main parameter influencing CAPEX, OPEX of CAROBS networks. These O/E blocks are used for optical signal conversion which is essential for burst buffering and most importantly for potential optical signal regeneration. Optical signal regeneration is crucial when a certain number of the optical signal amplification is met. When certain distance is crossed the optical signal is amplified otherwise it is difficult to convert it from optical to electrical domain. However, every amplification increases optical signal noise so at some point it is not possible the optical signal only amplify, but it must be regenerated. In terms of CAROBS deployment, a heuristic approach on the optical signal regeneration was investigated by Kozak et al. [15]. We suggested the CAROBS control plane redefinition such that we used the electrical buffering for the purpose of optical regeneration, OEO conversion. This paper disclosed issue of standard dimensioning approach based on the shortest path routing and LAUC-VF [16] for burst scheduling in CAROBS. Consequently, an in-depth analysis of CAROBS behaviour to quantify requirements on electrical buffering is carried out in this paper. The results of this study are formulated in a way that could be used in future research for an OBS deployment integrating the CAROBS framework.

The paper is organized as follows. Section 2. reviews recent work on OBS networks with a focus on buffering and the OBS loss-free paradigm. Section 3. briefly recalls the features of the CAROBS architecture and buffering behaviour, and redefines the architecture in terms of Queueing theory to capture the significant aspects of model traffic behaviour when buffering is assumed. In Section 4. , issues arising as a result of buffering are discussed in great details. In Section 5. , we describe the configuration of the simulator and the simulation approaches. Section 6. discusses the results of our simulations. Conclusions are drawn in the last Section.

2. Literature Review

The prime motivation of all-optical frameworks, including OBS, is to avoid an OEO grooming bottleneck, which would prevent high transmission speed. OBS uses sub-wavelength scheduling, so burst contentions causing performance deterioration might occur, even with optimized routing, reaffirming the need to minimize them. Recent studies designed time slotted OBS architectures as one way to avoid burst contention, see, e.g. [17] and [18]. Other studies returned to the principals of all-optical networks, with wavelength routing for bursts [19]. In most cases, these architectures rely on a ring topology or a mesh topology with a global in advance signalling to reserve a channel in an OCS-like manner, and some studies tackle synchronous transmissions over OBS network [20]. These solutions are either less scalable or less efficient from the perspective of network performance compared to dynamic just-in time signalling used in OBS and OPS [1]. All these architectures are compliant with the original OBS definition [3] and do not introduce any buffering.

Pavon-Marin et al. [21] 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 [21], the limiting factors of OBS are an inter-burst gap, a separate control wavelength and optical contention resolution. In order to overcome OCS for bursty traffic, the OBS paradigm must be changed [21]. The separate control channel and inter-burst gap cannot be omitted unless a time-slotted approach is used [17]. Therefore, buffering seems to be the only way to increase OBS network performance. Unfortunately, very little work has been done on OBS buffering.

Some early concepts use fiber delay lines (FDL) [22] and subsequent papers deal with dimensioning

FDLs [23]. Utilizing lengthy fibers is problematic on most premises, therefore some authors investigated scenarios utilizing electrical memories [12] and [13]. Among these works [12], [24] and [13], there is the CAROBS framework proposed by Coutelen et al. [13]. Coutelen et al. published a series of papers dealing with node architecture and its performance, but did not devote any attention to the dimensioning of a network consisting of CAROBS nodes. Traditionally, dimensioning of OBS networks has been carried out using M/M/k/k models [25] and [26]. However, this analytical model is not accurate as it does not reflect the streamline effect [27] and [28], which is why the burst blocking probability (BBP) seems to be higher than OBS mathematical models results. The streamline effect is the phenomenon unique to OBS networks wherein bursts traveling in a common link are streamlined and do not content with each other until they diverge [27]. When flows are merged, burst contention arises when there are incoming flows on the same wavelength. The ramification of the streamline effect is that a non-merging flow offering a given load level to a node should result in a BBP level according to M/M/k/k, however, thanks to the streamline effect, the BBP is 0. This result is known for classical OBS, but has not been studied for buffering OBS frameworks.

The buffering OBS is unique due to the so-called secondary contention. It occurs when a burst is scheduled from electrical memory back to the optical domain on a given wavelength at the same time as an incoming burst is requesting the same wavelength. In such a case, the new burst is buffered. It means that neither the M/M/k/k, nor the streamline effect model work for buffered OBS exclusively. Secondary contention was studied by Delesques et al. [29] using the Engset model. Their main concern was the buffer size dimensioning. However, they tackled buffering probability (BP) as well. BP is a comprehensive parameter of a buffered OBS network. It cannot be easily quantified by M/M/k/k models, with respect to the streamline effect, as for burst loss probability in a regular OBS network. Therefore, the M/M/k/k formulation with streamline effect and secondary contention must be combined when buffering OBS to provide the buffered OBS node model.

In this paper, we focus on a simulation approach to obtain experimental properties of buffering OBS nodes, i.e., the CAROBS node. These results can also be used for mathematical modelling.

In the next Section, we describe the CAROBS node architecture and internal processes that lead to buffering (loss-free) behaviour. We also describe the reformulation of a CAROBS node with respect to the queueing system terminology, in order to incorporate it to the proposed mathematical model described in Section 4.

3. CAROBS Model Description

The focus of this Section is on the CAROBS model with respect to the ways CAROBS resolves contention. CAROBS relies on electrical buffering as a way of avoiding burst loss. There are other concepts using electrical buffers [12] and [24], but all of these architectures are very complex . Our view is that CAROBS incorporates electrical buffering in an efficient way. It extends the classical Core node architecture and adds a buffering property using a software plane. It was defined by Coutelen in 2010 [13]. One of the most significant changes is how it merges Edge and Core node architecture into one CAROBS node. The CAROBS node architecture is depicted in Fig. 2. Thanks to the new architecture, CAROBS can ensure all-optical grooming via a new transmission mechanism called burst train which contains a number of bursts, here called cars, whose destination is along the same flow-path of the most distant destination node as seen in Fig. 1. The term flow-path represents a temporary lightpath, signalled by the JET mechanism, during the burst train. The burst train concept preserves the mandatory inter-car gap, to allow all-optical grooming. CAROBS all-optical grooming is achieved through the head drop as depicted in Fig. 1. Effective transmission in the form of burst trains is ensured by the Curbet Train Algorithm (CTA) [13] that optimally justifies car length so that the gap between two consecutive cars is equal to the mandatory inter-car gap. The burst train is signalled by one CAROBS header which contains the same information as the original Burst Header Packet [3] and adds the section containing information for each car [13]. A CAROBS car supports transmission of the same traffic as a burst in OBS. Each car contains aggregated data for only one destination edge node. In short, the burst trains concept improves OBS network performance [13].

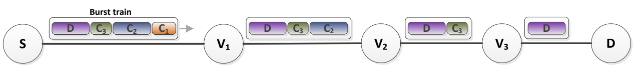


Fig. 1: An example of the CAROBS train structure containing cars for each intermediate node along the longest flow path. All optical grooming removes the head car(s) at intermediate nodes.

The CAROBS concept relies on the node architecture as depicted in Fig. 2. The WDM demultiplexer and multiplexer were omitted to make the illustration easier to read. The horizontal lines represent the input and output ports, and ports are labelled by λ. λ_1 represents the dedicated wavelength for the control channel and λ_x represents the wavelengths used for optical transmission. The CAROBS node architecture spans three logical layers. On the top there is the control plane that contains the *SOA Manager* which reads CAROBS headers and determines further node actions. The CAROBS node may either switch the whole burst train, groom-out the first car and switch the remaining part of the burst train, or, buffer the whole burst train because of contention. Based on this decision, the *SOA Manager* creates a set of instructions for the *SOA Switching Matrix* (MX) and forwards the CAROBS header to the next CAROBS node. The middle layer contains the aggregation and disaggregation ports for user traffic. The term user traffic represents traffic in the neighbourhood of the location of the CAROBS node. The most important block is the Media Access Control (MAC) on the middle layer. The MAC uses the CTA algorithm for car alignment in the burst train, stores the contenting burst trains in the internal electrical memory and re-aggregates the buffered cars. The bottom layer represents the physical layer where all cars are switched. It contains the MX that ensures the switching of the optical signal. If contention occurs the contenting burst trains are switched to the port dedicated for electrical buffering. These ports are directly connected to the O/E that convert the optical signal to the electrical domain where the contenting burst is buffered in MAC memory.

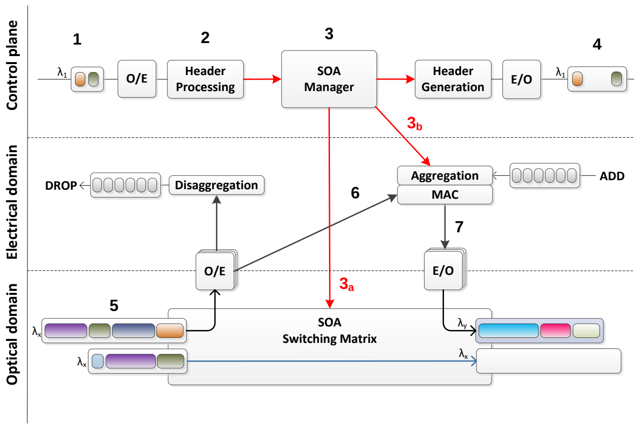


Fig. 2: CAROBS node resolves burst contention with recourse to an electrical buffer. The contenting burst train is sent to the MAC and stored until the output direction is available. The CAROBS header of the contenting burst is also modified as a result of delay buffering.

The contention resolution process is showed in Fig. 2. When a new CAROBS header reaches an input port of the CAROBS node (1) it is detected and processed (2). All relevant information is used by the *SOA Manager* which creates the MX configuration. If the burst train overlaps with a previously scheduled burst train, the burst train is buffered in order to avoid burst contention. In this case, the *SOA Manager* first calculates the buffering delay using the LAUC-VF (Latest Available Unused Channel with Void Filling) algorithm [16] then creates two instructions: one for the MX and the second for the MAC. The first instruction switches the contenting burst train to the dedicated port used for buffering (3_a). The second instruction informs the MAC for how long the burst train is to be buffered (3_b). Immediately following these two set instructions, the CAROBS header is scheduled and sent toward the next node. The CAROBS header is delayed by the same amount of time as the one by which the burst train is buffered in the MAC. When the contenting burst train arrives at the input port (5) it is deflected to the MAC and stored there (6). When the buffering time is up, the burst train is re-aggregated to the MX (7) and sent toward the next node.

3.1. Dimensioning Model

The description of the buffering process leads to the dimensioning problem of the CAROBS node. At first glance, the optimization of the CAROBS node might seem to be easy using the Erlang C formula to calculate the BBP, which is the same as BP. However, there are two perennial shortcomings: the Erlang C formula only works for systems with buffering before the service [30]. Moreover, the contenting burst cannot be buffered unless there are enough O/E blocks. It means that there is service before the buffering and this service must be a priori optimized before buffering can be optimized. Therefore, for the purpose of further discussion, we have reformulated the CAROBS node architecture, see Fig. 2, using tools of Queueing theory [30], see Fig. 3. Such a redefinition is vital to separate the buffering problem and the O/E block availabilities into two systems that can be tackled individually.

We define three building blocks, the *SOA Switching Matrix* that ensures optical signal switching and two Queueing systems (QS). For the sake of simplicity, we define them as the Input QS (IQS) and Output QS (OQS). The IQS tackles the contenting burst trains through a limited number of O/E blocks. The number of required O/E blocks depends on the IQS offered load. The offered load of the IQS can be quantified as $\alpha_{\text{BUF}} = \text{BP} \cdot \alpha$, where α represents the total node offered load, α_{BUF} represents the offered load to the IQS, and BP represents the buffering probability. Using the α_{BUF} values, the number of O/E blocks can be calculated with respect to the streamline effect which means the streamline effect evaluation must be carried out for less than five merging flows [27].

If there is more than five merging flows, the M/M/k/0 model can be applied [27]. Then we can use the Erlang B formula to obtain the BBP of IQS. The evaluation of the BBP enables us to obtain an approximation of the number of O/E blocks that are necessary to provide the loss-free mode. The OQS provides the burst train buffering and allows the traffic from connected networks α_{AGG} to be aggregated. The behaviour of both QS is driven by the *SOA Manager*. Since the

OQS receives burst trains in the form of an electrical signal it can store them in electrical memory. Current electrical memories provide only limited space, i.e. a limited number of burst trains can be stored. However, for the sake of simplicity and the CAROBS proposal [13] compliance, we assume that electrical memory is unlimited in this paper for all experiments.

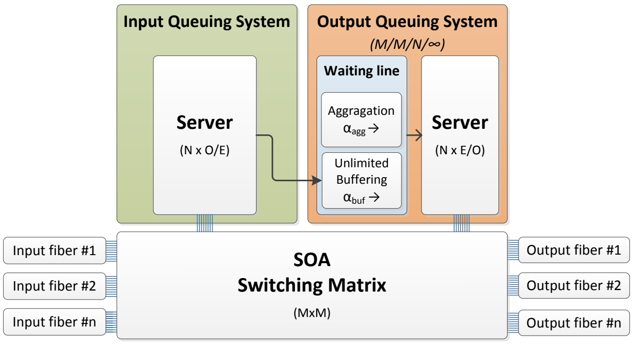


Fig. 3: Simplified block structure of the CAROBS node architecture in terms of QS [30]. It contains two QS and one SOA Switching matrix. The IQS is responsible for the optical signal detection and sends the burst trains to the electrical buffer once they are detected (O/E). The second QS controls the buffered trains and schedules them along the input traffic to the optical layer through a limited number of lasers (E/O) using LAUC-VF.

Every model relies on a number of approximations, the most crucial approximations in this analysis relate to the input traffic characteristics. The input traffic can be modelled using different input arrival processes and distributions of packet size. Some models are applicable only to a specific input traffic distribution or packet size distribution while some of them are more generic. In this analysis, we assume that the packets from the connected network arrive following a Poisson distribution at a rate of α packets per second so that the inter-arrival time between packets is a negative exponential distribution with parameter α. Depending on the car triggering [13], a burst train is created. CAROBS uses both triggering types (time, space) [13], therefore, car assembly tends toward Gaussian distribution asymptotically [26] according to the central limit theorem [31]. Using Kendall's notation [30], we classify the OQS as $M/M/N/\infty$ where N is the number of E/O blocks, see Fig. 3.

4. Dimensioning Problem Formulation

In the previous Section, the buffering process was described with its constraint represented by a limited number of O/E blocks. This Section deals with the traffic routing problem that is bounded to the number of O/E blocks. The key characteristics of the CAROBS framework is its loss-free mode of operation, i.e., no burst must be dropped.

In other words, there are always enough O/E blocks when contention occurs. On the other hand, O/E blocks are expensive from both an operational and installation perspective, hence it is reasonable to minimize their number. Minimizing the number of O/E blocks implies that the effects of merging flows and secondary contention must be a priori minimized. As long as the secondary contention is the only effect of merging flows, it can be taken care by minimizing the merging flow effects. Therefore, we next focus on the classification of merging flows and their impact on burst buffering.

Currently, traffic in all-optical networks is distributed in a network using both the routing and wavelength assignment (RWA) and grooming RWA (GRWA) approaches [32], [33] and [34]. In OCS networks, RWA is vital because there is no sub-wavelength scheduling; bandwidth sharing is achieved using traffic grooming in the electrical domain, so there is no contention in optical domain. In the design of buffer-less OBS networks, RWA is used extensively as well [8], [35], [36] and [37]. The performance of such a RWA algorithm is then modelled using burst loss probability (BLP). A classical way to write the RWA through a mathematical program is recalled in e.g., [38] and [39]. CAROBS ensures traffic grooming at intermediate nodes so we reformulate it such that we allow traffic grooming. To implement GRWA for a given network, the network topology is described as a graph $G(V, L)$ where V is the set of nodes and L is the set of directional links between any two connected nodes. Let D be the traffic matrix defining the amount of required bandwidth between any two nodes $s, d \in V$. Usually, the number of wavelengths is limited to $|\Lambda|$, assuming $\lambda \in \Lambda$. Then, the objective function jointly minimizing number of used wavelengths and nonprovisioned traffic is as follows:

$$\min \sum_{(s,d)\in V^2:s\neq d} \sum_{\substack{\ell\in L \\ \lambda\in\Lambda}} y^{sd}_{\ell,\lambda} + \theta \sum_{(s,d)\in V^2:s\neq d} e_{sd}, \tag{1}$$

where $y^{sd}_{\ell,\lambda}$ is a decision variable: it is equal to 1 if the required bandwidth flow ϕ from s to d is assigned on wavelength λ and link ℓ, and 0 otherwise. The e_{sd} is a variable representing how much of traffic could not be routed because there is not enough wavelengths in Λ to support all traffic D and θ is a objective function parameter. This objective function is subject to:
For all $v, s, d \in V$,

$$\sum_{\ell\in\omega^+(v)} \phi^{sd}_\ell - \sum_{\ell\in\omega^-(v)} \phi^{sd}_\ell = \\ = \begin{cases} D_{sd} - e_{sd} & \text{if } v = s \\ -D_{sd} + e_{sd} & \text{if } v = d \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

where $\omega^+(v)$ is the set of egress links of v and $\omega^-(v)$ is the set of ingress links of node v.

$$\sum_{s,d \in V} \phi_\ell^{sd} \leq y_{\ell,\lambda}^{sd} C, \qquad \lambda \in \Lambda, \ell \in L, \tag{3}$$

$$\sum_{s,d \in V} \phi_\ell^{sd} \leq C, \qquad \ell \in L, \tag{4}$$

$$\sum_{s,d \in V} y_{\ell,\lambda}^{sd} \leq 1 \qquad \lambda \in \Lambda, \ell \in L, \tag{5}$$

$$\phi_\ell^{sd} \geq 0, e_{sd} \geq 0 \qquad \{s,d\} \in V, \ell \in L, \tag{6}$$

$$y_{\ell,\lambda}^{sd} \in \{0,1\} \qquad \{s,d\} \in V, \lambda \in \Lambda, \ell \in L, \tag{7}$$

where C is the wavelength bandwidth (assumed to be the same for all wavelengths).

The only drawback of this formulation is that it does not take care of the merging flows and the sub-wavelength granularity which is allowed by OBS. The number of merging flows should be minimized as much as possible to maximize the occupancy of the simple, already merged flows. Hopefully, it can be done in the online mode using load balancing algorithms maximizing the streamline effect (SLE) [27]. However, such an algorithm corresponds to a heuristic, hence, it does not provide a globally minimal solution from the perspective of the number of O/E blocks. In other words, heuristics do not provide minimal solution which shows the minimal CAROBS requirements of studied network. Additionally, the number of O/E blocks depends on the characteristic of the node offered load, implication of M/M/N/0 model [30]. The incoming burst trains can be classified as a process with random inter-arrival intervals [26], therefore, it may result in infinite waiting in the electronic memory for a certain level of offered load. The infinite waiting is caused by the aforementioned premise of infinite memory, however, in real networks it would result in a burst loss because of limited electronic memory. Consequently, for the minimization of the number of O/E blocks, the offered node load must be engineered to avoid excessive buffering.

The conclusion of this Section is as follows. Both QS must be dimensioned properly, otherwise burst loss can be experienced. Both QS dimensioning relates to the maximal CAROBS node load. It can be formulated as the input traffic intensity ρ, so that $\rho \equiv \alpha/\mu$. The CAROBS node stability condition is $\rho < 1$ which can be written as $\alpha < \mu$ [30]. Here, α stands for total node offered load and μ represents the node intensity of service, i.e., how much traffic a node can transmit. The node offered load α is equal to the sum of offered loads from each tributary flow. It is worth noting that the stability condition applies to the system with merging flows, otherwise applies to the SLE. For the SLE, the stability condition changes to $\rho \leq 1$.

In order to stabilize the GRWA formulation, we must modify Eq. (3) such that it limits the traffic routed to each output link and does not exceed the value of ρ for various numbers of merging flows. The constraint is reformulated as:

$$\begin{gathered} \sum_{(s,d) \in V^2} \phi_\ell^{sd} \leq y_{\ell,\lambda}^{sd} \cdot C \cdot K \\ \lambda \in \Lambda, \ell \in L_{\text{selected,v}}, v \in V, \end{gathered} \tag{8}$$

where L_{selected} represents the set of outgoing links of the merging node V, e.g., ℓ_0 in Fig. 4, which concentrates traffic from a number of merged flows and K is the coefficient of stationary threshold that ensures that the egress link is used efficiently $C \cdot K \to \rho_{\max}$, i.e., no excessive buffering nor burst loss occurs.

Constraints Eq. (8) imply that the maximum node load is limited. Then the stability condition is valid, additionally the electronic memory is not overloaded.

5. Simulations

Following the discussion on the optimization of the number of O/E blocks issues, BP cannot be estimated using either the M/M/k/k model, or the SLE, because both provide information about BBP but not about BP. There is a clear relation between BP and BBP, but the main difference is that BP is influenced by secondary contention. The BP value can be quantified either mathematically or empirically using simulations. In this paper, an approximation model relying on simulations, prior to the design of a mathematical model in the future, is discussed. We focus on the basic node behaviour under various conditions, using the topology depicted in Fig. 4. The most important node, the node under study, is marked as merging node v, see Fig. 4. There is also destination node d where all traffic flows, from sources $s_\bullet$, are destined. Traffic flows originate in source nodes. Four scenarios with different number of sources are evaluated. Two to five merging flows are evaluated. The maximum of five merging flows was chosen because the maximum node degree that is considered is six, i.e., five merging flows in [40]. Simulations were carried out using OMNeT++ simulator and CAROBS models [15]. Source nodes $s_\bullet$ were supplied with traffic generated according to a Poisson distribution. The generated payload packets of constant size (100 kb) defining the flow were supplied to aggregation queues to generate bursts. It is assumed that electrical storage capacity is unlimited. JET (Just Enough Time) [3] was used as a signalling protocol and LAUC-VF algorithm [16] for burst assembly.

Traffic analysis is quite comprehensive if one wants to reach a specific level of accuracy. In order to obtain accurate results, the number of simulations must

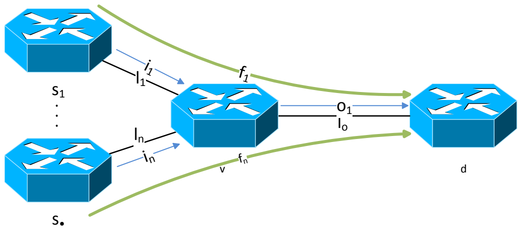


Fig. 4: The elementary topology used for one node behaviour evaluation. The number of sources was changed as is depicted here by $s_1, \ldots, s_\bullet$.

be as high as possible because the results accuracy is achieved through the repetition of identical simulations and by changing the input load patterns. However, the number of repetitions implicate the total simulation time; therefore, a limited number of simulations should be used.

In our simulations, we carry out 25 identical simulations with different patterns of node offered load. The main task of the simulations is to verify the impact of the number of merging flows (MF) and node load α on the buffering probability $\mathrm{BP}(\alpha, \mathrm{MF})$ and buffering delay $\mathrm{BD}(\alpha, \mathrm{MF})$ of a buffered burst train. The node load α is equal to the sum of loads offered by each tributary flow. Then, the average maximal offered load provided by each source is $1/(\mathrm{MF}+1)$ erl. The term average maximal offered load represents the average value of offered load among the identical simulations for one simulation at the given node offered load α.

In addition to the number of merging flows and the node load, an evaluation for wavelength data rate 1, 10 and 40 Gbps is performed. Wavelength data rate 100 Gbps was simulated, but the difference of results for 40 and 100 Gbps was negligible thus the result for 40 Gbps wavelength data rate are presented. Additionally, only the on-off keying modulation format was implemented into CAROBS model; therefore, results for 100 Gbps are not conclusive and presented. In Subsection 6.2. , we investigate further the O/E block sharing in WDM networks to verify the impact of the wavelength number $|\Lambda|$ on $\mathrm{BP}(\alpha, \mathrm{MF}) \rightarrow \mathrm{BP}(\alpha, \mathrm{MF}, |\Lambda|)$ and $\mathrm{BD}(\alpha, \mathrm{MF}) \rightarrow \mathrm{BD}(\alpha, \mathrm{MF}, |\Lambda|)$. We vary the number of wavelengths $|\Lambda|$ from 1 up to 60.

6. Results

First, we deal with simulations restricted to only one wavelength where we vary wavelength data rates. Therein, we first focus on the stability of measured parameters and their confidence. Based on the results we formulate recommendation for the number of O/E blocks in order to ensure loss-free mode of operation. Also, these results open question about viability of one wavelength systems, i.e., wavelength sensitive O/E blocks.

Subsequently, in Subsection 6.2. , we evaluate the same simulation scenario for multiple wavelengths (WDM mode of operation) and colour-less O/E blocks. These results favors the WDM in CAROBS networks because WDM mode decreases number of O/E blocks that are necessary for the same load as for one wavelength scenario significantly. Additionally these results open a very promising deployment scenario that is unique for CAROBS.

6.1. One Wavelength Evaluation

One-wavelength transmission systems were common before the emergence of WDM systems. Here we return to the one-wavelength system because of its simplicity, i.e., less degree of variance in the analysis. Less degree of variance means a smaller number of parameters that can change. Such a (lower) number of parameters is vital for the stability discussion of results as other parameters are fixed. The one-wavelength analysis consists of two main steps. In the first step, we remedy the number of identical simulations, so the following results are a trade-off between accuracy and the overall time of running simulations. In the second step, we repeat the predefined simulation n times and then we evaluate the results.

In order to find the trade-off between accuracy and overall simulation running time, simulations for three different node loads $\alpha = \{0.1, 0.5, 0.9\}$ erl are conducted. For each of these three-node loads, 2,000 simulations with different offered load patterns are performed. Additionally, we conduct this analysis for data rates 1, 10, and 40 Gbps. Only the stationary simulations are used, and simulations are tested using the mathematical tool of hypothesis testing. The signal is stationary when the values of BD and BP do not depend on time, i.e., statistical properties do not change during the simulation. This test is applied to the whole simulation time interval and in addition to the subintervals. Each sub-interval contains 120 samples. In the test, it is assumed that the time dependent values of BD and BP can be approximated using a linear regression line, which is quantified by time vector X, the coefficients of linear regression b_0, b_1, and the coefficient of linear regression error e_i which must be minimal. Then, we can formulate a null hypothesis $H0$ claiming that the signal is stationary if every sub-interval is stationary. Sub-interval stationarity is characterized by coefficient $b_1 = 0$. If $b_1 \neq 0$, then such a sub-interval is not stationary, so the whole time interval, i.e., the simulation cannot be used for further stability analysis. The core of the linear regression analysis is shown in Eq. (9), Eq. (10), Eq. (11) and Eq. (12).

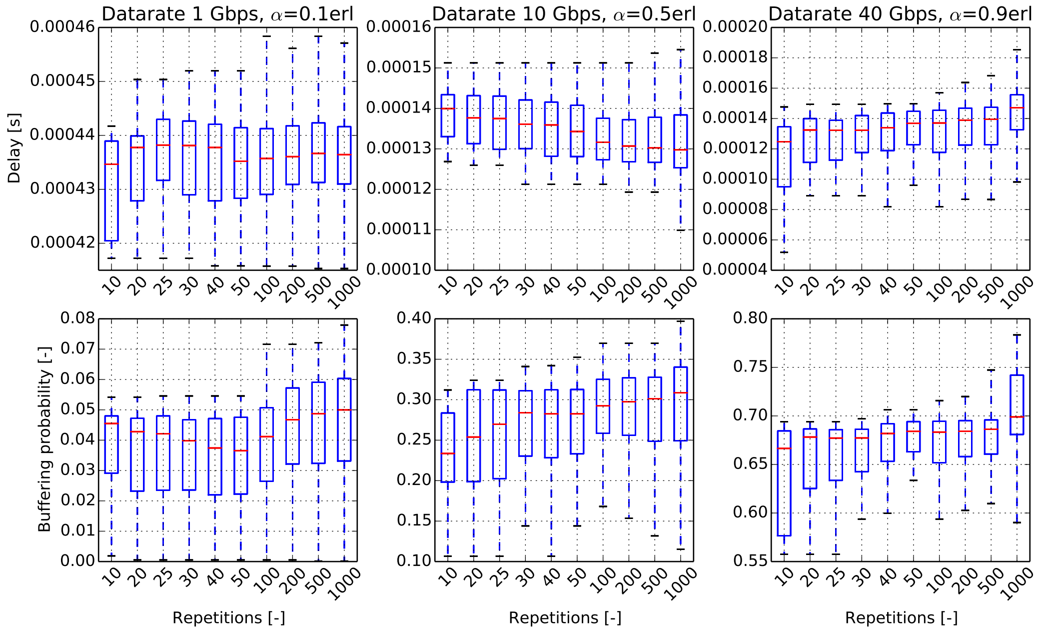


Fig. 5: Statistical properties of BD and BP captured using boxplots for various node loads and various data rates. In the upper row, characteristics of buffering delay are depicted. In the bottom row, characteristics of buffering probability for a different number of identical simulations are shown.

$$Y_i = b_0 + b_1 x_i + e_i \qquad i = 1, 2, \ldots, n, \tag{9}$$

$$b_1 = \frac{n \sum\limits_{i=1}^{n} x_i^2 Y_i - \sum\limits_{i=1}^{n} x_i \sum Y_i}{n \sum\limits_{i=1}^{n} x_i^2 - \left(\sum\limits_{i=1}^{n} x_i\right)^2}, \qquad b_0 = \frac{\sum\limits_{i=1}^{n} Y_i - b_1 \sum\limits_{i=1}^{n} x_i}{n}, \tag{10}$$

$$s^2 = \frac{\sum\limits_{i=1}^{n} Y_i^2 - b_0 \sum\limits_{i=1}^{n} Y_i - b_1 \sum\limits_{i=1}^{n} x_i Y_i}{n-2}, \tag{11}$$

$$\frac{|b_1| \sqrt{\sum\limits_{i=1}^{n} x_i^2 - n\bar{x}^2}}{s} \geq t_{n-2}(\Psi), \tag{12}$$

where n is the number of verified samples in the sub-interval and the number of sub-intervals for the hypothesis testing of the whole simulation interval. Then, the decision on stationarity is valid with a level of confidence Ψ. If the critical value Eq. (12) is higher than the coefficient of Student's distribution, the hypothesis $H0$ does not apply, i.e., BD or BP is not stationary and the simulation cannot be used for further evaluations. The valid set of simulations is then used for the evaluation of the number of identical simulations. This approach is also used in the next analysis of the maximal node load.

In order to find the minimal number of identical simulations, which are necessary, we perform 2,000 simulations for each case (combination of load and data rate) and evaluate these results. The statistical properties of datasets representing various numbers of identical simulations can be seen in Fig. 5. The statistical properties do not change after 1,000 identical simulations; therefore, for the sake of readability, we did not depict cases for more than 1,000 identical simulations in Fig. 5. One can see that in most cases after 25 identical simulations the mean value and variance do not change significantly against their values with 1,000-simulation case. Therefore, we chose to have 25 identical simulations for all our simulations in the paper. As long as there are only 25 identical simulations, the results can be corrected using the coefficients of Student's distribution.

The impact of the number of merging flows to the BD and BP is an extremely important aspect of the analysis which is carried out using the dataset containing 2,000 simulations. For the sake of simplicity, only the case for the node load 0.5 erl is depicted, however, all other simulation schemes led to the same conclusion that BD does not depend on the number of merging flows, see Fig. 6, only on the node load, see Fig. 8(a). This conclusion comes from the Poisson character of the merged flows. Therefore, in the delay analysis, we can assume $\mathrm{BD}(\alpha, \mathrm{MF}) \equiv \mathrm{BD}(\alpha)$.

The same dataset of 2,000 different patterns was used for the BP analysis with the results for node load 0.5 erl depicted in Fig. 7. Other node load results led to the same conclusion. According to the results depicted in Fig. 7, it can be seen that above 2 MF the difference of BP is negligible, therefore, we can only define BP for two or more MF as two different parameters in

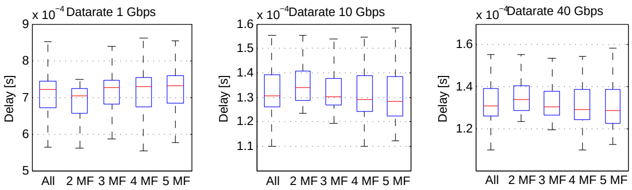


Fig. 6: Buffering delay test of dependance for node load α = 0.5 erl showing Buffering delay does not depend on the number of merging flows. The routing policy does not avoid scenarios with a higher number of merging flows for the same level of offered load when the end-to-end delay is the main concern.

the next analysis. This is indirect contradiction to the M/M/k/k with an inclination to the SLE for small MF scenarios.

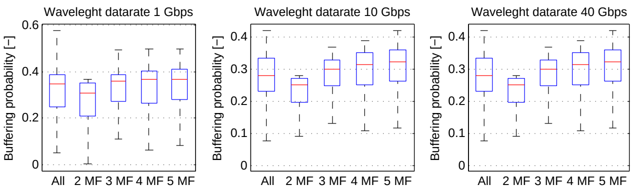


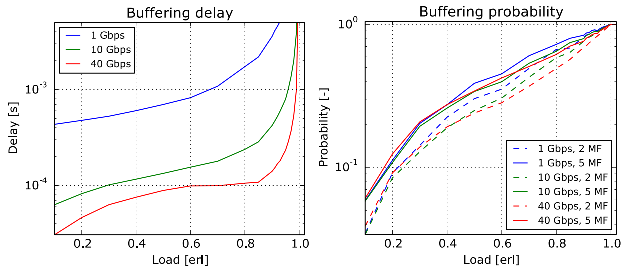
Fig. 7: Buffering probability dependance test on the number of merging flows. The test was carried out for the node load α = 0.5 erl. This test shows that the Buffering probability does not depend on the number of merging flows for $MF \geq 3$.

In the performance analysis of the CAROBS system using one wavelength, 25 schemes were performed with a variety of offered load patterns for load $\alpha = [0.1; 1.02]$ erl with equidistant step 0.02 erl for $\alpha = [0.1; 0.95]$, and with step 0.01erl for $\alpha = [0.95; 1.02]$ erl. The scheme using 2-5 MF and three data rates 1, 10 and 40 Gbps of a wavelength was retained and BD and BP stationary tests were evaluated in order to obtain the stationary threshold K which defines the maximal load when buffering is bounded. The values determining the stationary thresholds are captured in Tab. 1. Therein, a column F_{BW} is added to expresses the stationary threshold in terms of the bandwidth that must be free to avoid excessive buffering.

Tab. 1: Table of load thresholds and spare bandwidth. F_{BW} represents the spare bandwidth, which cannot be used to keep the node stable in a long-term perspective.

	1 Gbps		**10 Gbps**		**40 Gbps**	
MF	K	F_{BW}	K	F_{BW}	K	F_{BW}
2	0.89	110 Mbps	0.93	700 Mbps	0.96	1.6 Gbps
3	0.88	120 Mbps	0.89	1.1 Gbps	0.89	4.4 Gbps
4	0.88	120 Mbps	0.89	1.1 Gbps	0.89	4.4 Gbps
5	0.87	130 Mbps	0.88	1.2 Gbps	0.88	4.8 Gbps

The values of BD(α) and BP(α, MF) are seen in Fig. 8. The differences among BD(α) for various wavelength data rates in Fig. 8(a) are shown. When the end-to-end delay is a routing concern, it can be seen that the node load cannot exceed $\approx$ 0.9 erl, otherwise BD exponentially increases. Further, the value of the load $\approx$ 0.9 erl is equal to the stationary threshold which means that the node could not ensure the loss-free mode permanently. It would eventually lead to burst loss. The second monitored parameter BP(α, MF) is seen in Fig. 8(b) where we depict only two and five MF cases. The notably high BP is evident even for the low node load from this figure. Such a situation is not vital for production networks; therefore, we assume that wavelength dependent optical detector (O/E) blocks do not pave the path to the CAROBS in WDM networks. On the other hand, this situation provides very useful data that can be used for further analysis as an upper bound when the number of O/E blocks is the main concern.



(a) (b)

Fig. 8: The BD and BP rely on the value of the offered load. Below 0.9 erl the BD is in scale of μs, however, above 0.9 erl, it significantly increases. The BP is more proportional to the value of the offered load α. Therefore, when engineering the number of regenerators, BP is the main objective.

The accuracy and results of BP are crucial when estimating O/E blocks. Each O/E block can be used by only one burst at a time and only one burst train can come at a given time period because wavelength can carry only one single burst train at a moment. Subsequently, the number of buffered bursts depend on the offered load α and the number of MF, BP(α, MF). The BP(α, MF) specifies the probability a new incoming burst train will be blocked by another burst train (burst contention); in the worst-case scenario, the new incoming burst train can be blocked by a rescheduled burst train (secondary contention) [41]. The worst-case scenario results in the corner case of equal numbers of O/E blocks and MF, and the O/E block measurement is depicted in Fig. 9. Notice, it is necessary to install at least $MF - 1$ O/E blocks even for a low load. These graphs quantify the O/E block requirements so they can be used in further studies of CAROBS GRWA. The O/E block measurement reveals a high demand of the number of O/E blocks, even for a low load, therefore, it is not viable for real CAROBS deployment in WDM networks where deployment requires a specific number of O/E blocks per wavelength depending on the α at the wavelength.

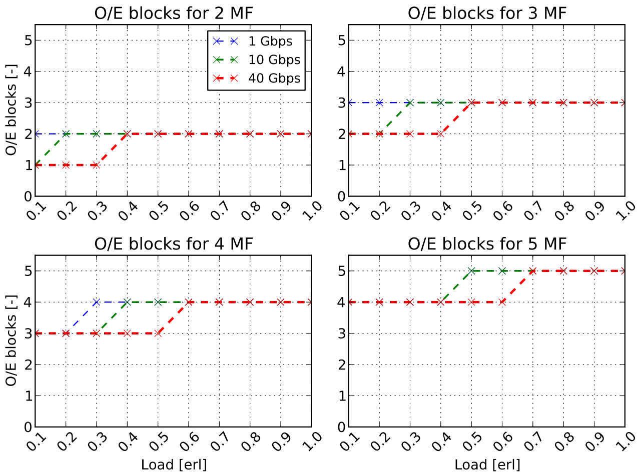


Fig. 9: Dependance of the number of O/E blocks for various MF scenarios and wavelength data rates. The most resilient case is for 2 MF. This scenario is also the cheapest, though sometimes at the expense of wavelength greediness. The evaluation of $R(\alpha, MF)$ is calculated from Fig. 8(b).

The total number of O/E blocks required for the CAROBS network and given traffic D can be calculated through the CAROBS GRWA extension which gives information about virtual routing (different routing for different wavelengths). Each wavelength can have a different number of merging flows (MF_λ) and a different node offered load α_λ. The evaluation of the number of O/E blocks can be formulated as follows:

$$\sum_{\substack{v \in V \\ \lambda \in \Lambda}} R(\alpha_{v,\lambda}, \mathrm{MF}_{v,\lambda}), \qquad (13)$$

where function R represents the graphs depicted in Fig. 9, i.e., the requirement on the O/E blocks to deliver the loss-free mode of operation.

Such a formulation can be used for CAPEX or OPEX studies where it can define the part of objective function in order to minimize monetary sources while maintaining an appropriate quality of transmission.

6.2. Multiwavelength Evaluation

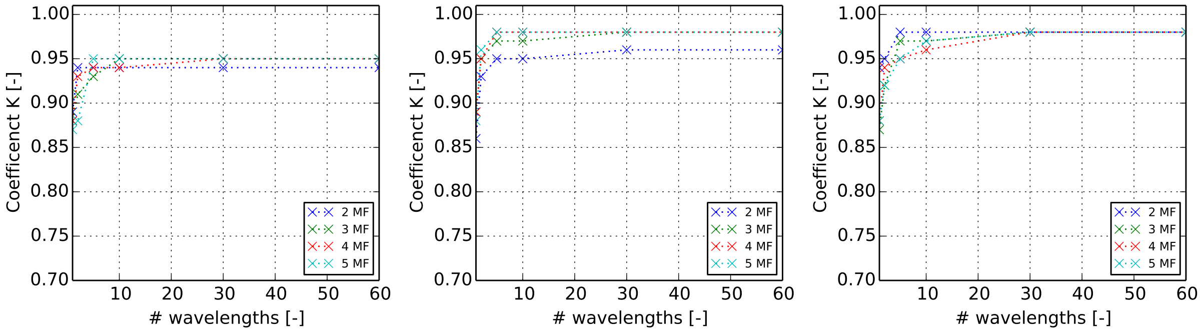
Following the results obtained in the previous Section, the focus shifts to only the BD, BP, and colourless O/E blocks. First, the stationary threshold of the CAROBS WDM system with a various number of wavelengths $|\Lambda|$ will be evaluated the the required number of O/E blocks will be enumerated. The term "Load" will be used in all figures, however, the meaning is slightly modified compared to the previous Section where it meant the total utilization of one wavelength. From now on, the term "Load" represents the overall utilization of all wavelengths in a specific link – link utilization. For example, a link supporting 10 wavelengths, where only one wavelength is utilized by a 1 erl traffic, according to the notation used in the previous Section, means that Load is equal to 0.1 erl. K is redefined the same way as Load.

The stationary threshold of CAROBS WDM was evaluated based on the dataset of the CAROBS WDM system where the $|\Lambda|$ was varied, and the number of merging flows MF and node offered load α was changed. The accuracy of each step, as defined in Subsection 6.1. , is evaluated using the mean value analysis (MVA) approach. The MVA was carried out so the final value is uncertain with less than 5% of probability. The dependance of the coefficient $K(|\Lambda|)$ is illustrated in Fig. 10.

The inclination of coefficient $K(|\Lambda|)$ to the value one is seen; however, in the studied range of wavelengths it does not meet it. It results into the gap of bandwidth F_{BW} that cannot be used for static traffic, but this gab of bandwidth can be used for frequently bursting short term flows which cannot result in excessive buffering. The values of coefficient $K(|\Lambda|)$ delimit the working area where the CAROBS WDM system can be provisioned. Subsequently, the graphs of BD and BP are depicted in Fig. 11. BP is captured for two and five MF in Fig. 11a), Fig. 11b) Fig. 11c), $\mathrm{BD}(\alpha, |\Lambda|)$ is depicted in Fig. 11d) Fig. 11e) Fig. 11f) without respect to the number of MF, because of the Poisson character of merging flows, see Subsection 6.1. Both BP and BD improved significantly as the number of wavelengths $|\Lambda|$ increased. This improvement in values of BP and BD is an excellent indicator that further research on colour-less O/E blocks is the right direction.

The gap between the two and five MF scenarios is worth studying as it takes on importance as the wavelength data rate increases. The gap is the direct result of SLE, i.e., suppressed secondary contention. Presumably, it can be used to minimize the number of deployed O/E blocks in the network. Then the objective can be formulated as minimization of MF and maximization of the stream lining. The contribution of this Section is the prove that SLE is highly important for the CAROBS node and its performance.

The number of O/E blocks relates to BP, and the graphs are depicted in Fig. 12. The one-wavelength scenario is captured here to depict the upper bound described in the previous Section. We can see that O/E blocks sharing among wavelengths can significantly reduce their necessity for the same level of offered load. It is significant to note that it is not necessary to install any O/E blocks for buffering up to a specific level of node offered load. Such a threshold can be used in order to design simple CAROBS nodes with minimal requirements, and such a node could be deployed into distant areas. On the other hand, this approach al-



(a) Wavelength datarate 1 Gbps. (b) Wavelength datarate 10 Gbps. (c) Wavelength datarate 40 Gbps.

Fig. 10: Dependance of reduction coefficient K on the number of wavelengths. The value of coefficient $K_{bps}(\lambda, |\Lambda|) \to 1$ is not equal to one, i.e., there is some free capacity necessary to keep the system stationary.

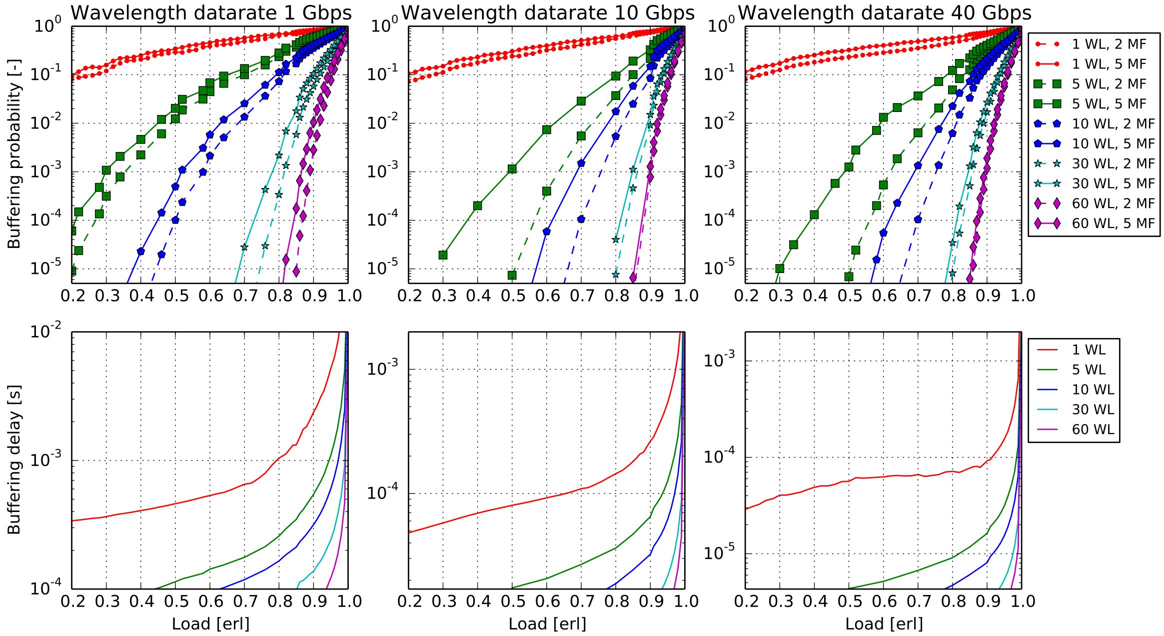


Fig. 11: A comparison of CAROBS using the WDM system. The upper set of figures depict the buffering probability for six different wavelength sets and two and five MF. The lower set of figures captures the average buffering delay with no respect to the number of MF. Both sets offer clear evidence for shared O/E blocks deployment.

lows designing CAROBS nodes which tackle most contentions.

The shared O/E blocks approach allows extension of CAROBS nodes deployment with no O/E blocks which is promising for networks with centralized buffering, as it allows traffic routing without any O/E blocks for contention resolution at a particular node. Geographically extensive deployments, with some nodes low loaded nones can be deployed more cheaply and easily. That notwithstanding, more powerful nodes can be installed in data centers allowing contention resolution through O/E blocks. It is important in future studies to return to the regeneration of optical signal because of optical impairments and these results give us a good starting point. This Section showed that the CAROBS WDM with shared O/E blocks has minimal requirements on O/E blocks for contention resolution. Therefore, it is worth investing more research into optimal routing and O/E block installation in further work.

6.3. Highlight of Results

In this Section, the analysis based on OMNeT++ simulations was split into two Subsection 6.1. and Subsection 6.2. In the first Subsection we mainly focused on the simulation condition in order to ensure valid outputs and defined the CAROBS stability condition. Satisfying these conditions, we carried out information on CAROBS behaviour for wavelength selective O/E blocks. Based on these results we concluded that CAROBS WDM relying on wavelength selective O/E blocks will present very high CAPEX and OPEX, i.e.,

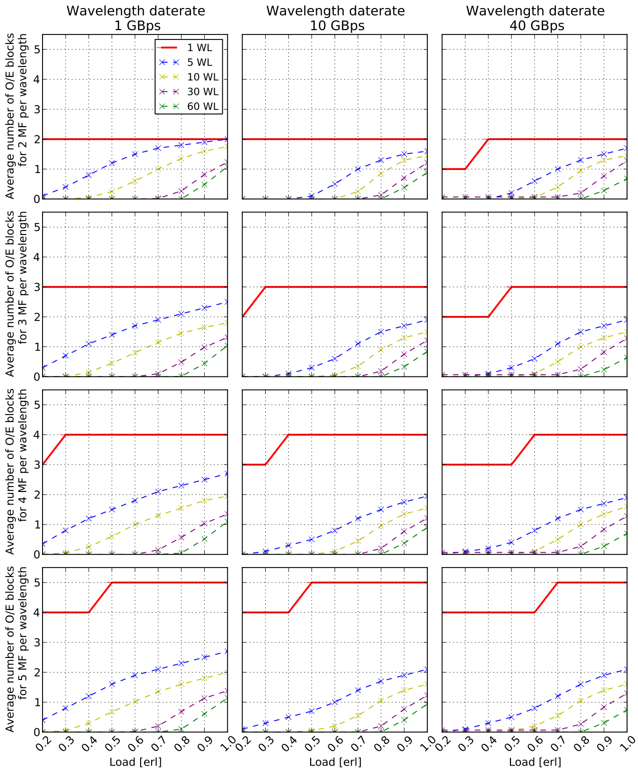


Fig. 12: Estimation of the average number of O/E blocks per wavelength with respect to the egress port load. The higher the number of wavelengths shared by one O/E block, the lower the total number of O/E blocks. The upper boundary for the system containing a higher number of wavelengths is lowered because it is over the threshold K, i.e., a load that we do not want to reach.

it raises motivation for CAROBS WDM using colour-less O/E blocks.

CAROBS WDM based on colour-less blocks analysis was carried out in Subsection 6.2. This analysis shows very significant O/E blocks amount reduction. Very interesting property of CAROBS networks is that it allows traffic routing without any O/E block at some nodes thus make the CAROBS network maintenance easier.

7. Conclusion

The feasibility of an OBS deployment has been proven by recent prototypes developed by vendors [4], but, still, there is no large scale deployment of OBS networks. The initial reason, related to burst loss, was addressed by the CAROBS framework of Coutelen et al. [13] and resolved by the loss-free paradigm. Nevertheless, geographically extensive deployment for burst traffic as we can see in access or metropolitan networks is not possible since the optical signal degrades before it is received by the end node. This problem was outlined in CAROBS [15], but a thorough study was not carried out thus we went through these lacking experiments and brought detail analysis of CAROBS behaviour which we plan to use for CAROBS GRWA formulation.

GRWA formulation is very useful for CAROBS. CAROBS is the only OBS framework that allows traffic disaggregation at intermediate node, so it would be inefficient to use RWA strategy as is usually done for OBS. Consequently the OBS seems to be inefficient when compared to OCS; however, both paradigms are good for different traffic characteristics, i.e., network topologies thus it is not fair to compare them under the assumption that one can replace the other one. CAROBS can perform very well in access networks with a lot of bandwidth granularities that are merged. Also CAROBS can be used for construction of very simple nodes that can be placed in outlaid areas with almost no maintenance.

As we believe in OBS and CAROBS networks, we would like to focus our future work on GRWA for CAROBS WDM using colour-less O/E blocks in order to design optimal traffic routing that allows to cross geographically significant installations as well as complex metropolitan mesh networks.

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About Authors

Milos KOZAK received the M.Sc. and Ph.D. degrees in electrical engineering from the Czech Technical University in Prague, in 2009 and 2015, respectively. Since 2009 until 2012, he tought optical communication systems and data networks with the Czech Technical University in Prague. His research interest is on the application of high-speed optical transmission systems in a data network. Particularly regenerators placement in all optical networks.

Brigitte JAUMARD holds a Concordia University Research Chair, Tier 1, on the Optimization of Communication Networks in the CIISE - Concordia Institute for Information Systems and Engineering - Institute at Concordia University. She was previously awarded a Canada Research Chair - Tier 1 - in the Department of Computer Science and Operations Research at Universite de Montreal. She is an active researcher in combinatorial optimization and mathematical programming, with a focus on applications in telecommunications and artificial intelligence. Recent contributions include the development of efficient methods for solving large-scale mathematical programs, and their applications to the design and the management of optical and wireless, access and core networks. In Artificial Intelligence, contributions include the development of efficient optimization algorithms for probabilistic logic (reasoning under uncertainty) and for automated mechanical design. B. Jaumard has published over 150 papers in international journals in Operations Research and in Telecommunications.

Leos BOHAC received the M.Sc. and Ph.D. degrees in electrical engineering from the Czech Technical University, Prague, in 1992 and 2001, respectively. Since 1992, he has been teaching optical communication systems and data networks with the Czech Technical University, Prague. Since 2014, he holds position of associate professor with Czech Technical University, Prague. His research interest is on the application of high-speed optical transmission systems in a data network. He has also participated in the optical research project CESNET - the academic data network provider to help implement a long-haul high-speed optical research network. Currently, he has been actually involved in and led some of the projects on optimal protocol design, routing, high speed optical modulations and industrial network design.