Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Telecommunication Engineering

DISSERTATION THESIS STATEMENT

Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Telecommunication Engineering

Efficient Control, Routing, and Wavelength Assignment in Loss-Less Optical Burst Switching Networks

by

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1 Introduction and related work

In the early 1980s a revolution in telecommunications networks began and spawned by the use of a relatively unassuming technology: fiber optic cable. Since then, the tremendous cost savings and increased network quality has led to many new services delivered over networks using optical fibers, and many new benefits of very fast network are only beginning to be realized. In the early 90", telecommunication networks were used for voice calls, dial-up was the greatest development, and first very low rate international peerings were emerging in order to enable data communication between states. Today, on the other hand, one can use an ordinary cellphone in order to access Internet with download speed around 150 Mbps[1], and recent standards specify even higher data rates. This download speed is almost negligible compared to optical access networks where the transmissions speeds can be symmetric and download speed can be 10 Gbps [1].

These extraordinary speeds in access networks are necessary due to many factors: the tremendous growth and penetration of the global communication network called Internet and its service World Wide Web (WWW) which is the main source of information for Internet users. However, the WWW is starting to be overcome by applications using communication capabilities provided by Internet. The impact of applications on the required bandwidth is caused by their number. Each user can have more devices where some applications can be installed (phone, tablet, etc.), and there can be more than just one application connected to the Internet at the same time. Therefore, the amount of data transmitted in Internet service providers (ISPs) networks is continuously increasing even though it was assumed the bandwidth usage is going to culminate because the Internet penetration has been saturated in developed world [2].

Thanks to the technological advances, cost of the bandwidth has been continuously reducing. Additionally, the deregulation of the classical market of voice and data services initiated competition which in turn has resulted in lower end user costs and faster deployment of new technologies and services. This deregulation has also resulted in creating a number of new start-up service providers as well as companies providing equipment to these service providers. As one can see, this development drives the lust for more bandwidth in the network, so the bandwidth requirement has no sign of abating in the near future.

These factors have driven the development of high-capacity optical networks and their remarkably rapid transition from research laboratories into commercial deployment. The twisted pairs would never allow transmitting as high data rates as one wavelength can support in optical networks for long distances. Dealing with such a huge capacity optical networks provide, an efficient mechanism must be defined. Therefore, this thesis is dealing with optimal traffic routing, and control mechanisms in optical networks of future.

1.1 All-optical switched networks

The future optical networks will use a technique called *bypass* [3] which enables to switch an incoming light at certain wavelength to a defined output port, and if wavelength conversion (WC) is used wavelength can be changed as well. Optical networks using optical bypass can considerably reduce propagation delay due to electronic processing is avoided. Efficient use of optical network is achieved due to Wavelength division multiplex (WDM). The ramification of all-optical network is captured in Figure 1 where one can see that the interoperability with legacy or non-optical technologies is realized by edge nodes that convert communication protocols of the adjacent network to the communication system of the all-optical network.

There are three popular switching paradigms that have been proposed for the all-optical networks: Optical Circuit Switching (OCS), Optical Packet Switching (OPS), and Optical Burst Switching (OBS) [4]. In OCS an end-to-end *lightpath* is established between a source node and a destination node for the entire session which can last a few seconds and more. Lightpaths avoid opto-electronic (O/E) conversions; therefore, the end-to-end delays considerably decreases and optical grooming is not possible. In the OPS, packets from the client network are directly switched in the optical domain along the path

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[1]This is current maximal download speed in a Long Term Evolution (LTE) network.
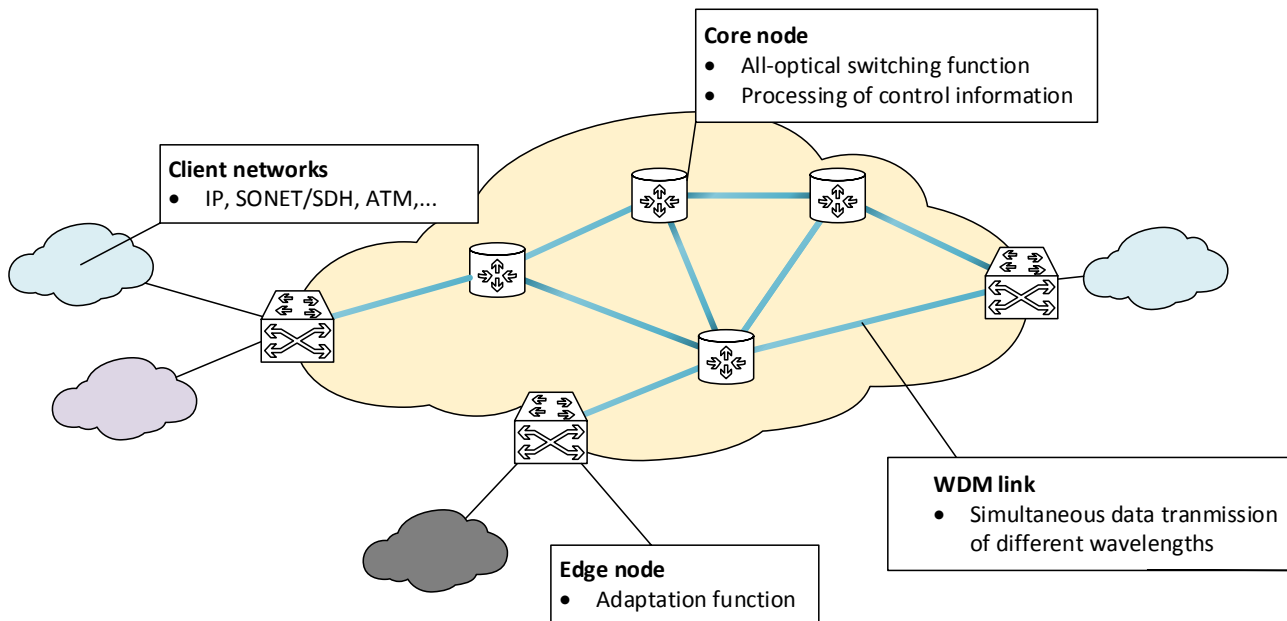
Figure 1: Generic architecture of optical DWDM network.

as it is common in Internet Protocol (IP) networks, but the IP networks use electronic switches with electronic memory for congestion avoidance. The optical random access memory (RAM) memories are not ready for production deployments hence packet loss can occur in OPS networks. The third switching paradigm is OBS proposed in order to overcome the deficiencies of both OCS and OPS. Also, OBS is seen as a technology to support all-optical switching in the Internet before OPS is ready. The benefit of OBS and OPS over OCS is no need to dedicate the capacity of a wavelength for the entire session between a pair of nodes. This is extremely important for sessions that do not fully use capacity of a wavelength. Moreover, OBS is more viable than OPS because packets, for OBS bursts, does not need to be buffered at the intermediate nodes, so OBS can deliver lower latencies. In the following section, the all-optical paradigms are discussed in more detail to give reader better overview of transmission principles.

1.2   Optical Burst Switching

OBS provides statistical multiplexing in optical domain, i.e., optical grooming. The principle of OBS is the transmission of the data bursts, which are transport units that carry multiple frames or packets from client network, and just in time channel signaling. These bursts are switched all-optically by an Optical Cross-connect (OXC) using information carried in burst header packet (BHP). The BHP is transmitted on a dedicated control channel and precedes the burst in order to give some time the core node to process this BHP and configure OXC. Based on the information carried by the BHP the intermediate nodes reserve particular switching resource for the duration of the data burst. This time between BHP and burst is called *offset time (OT)*, and it is proportional to the number of hops and Quality of Service (QoS). An OBS network is depicted in Figure 2.

The efficient bandwidth allocation was unachievable by OCS technology. Due to bursts are larger than OPS packets, processing overhead is reduced and the technology requirements for switching fabric and processing are not so hard. The duration of a typical burst can last from some μs to several hundreds of ms. OBS presents enormous advantages over OCS, and is easier to implement compared with OPS. Nevertheless, OBS is not ready for deployment, and if there is an technological jump enabling optical RAM memories OBS will never go to market.
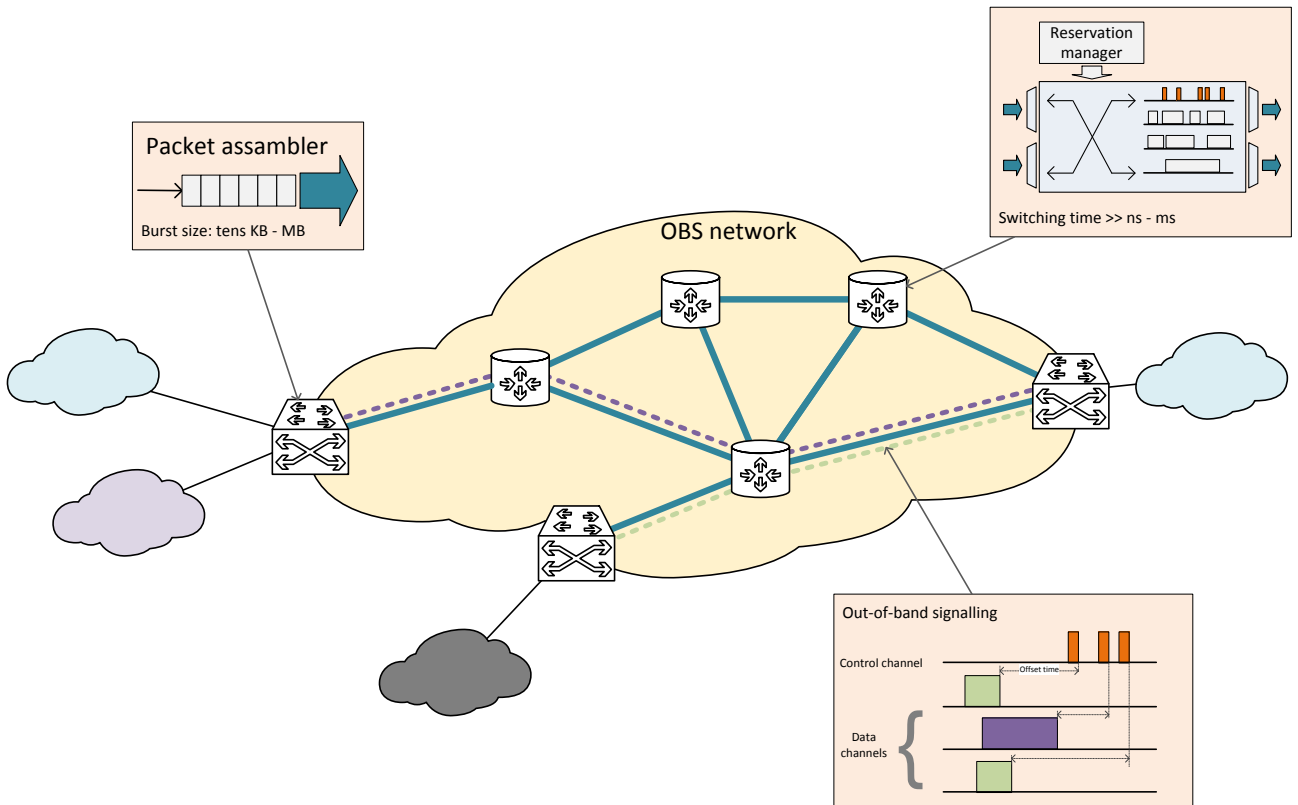
Figure 2: OBS network (Picture adapted from [5]).

1.3 Loss-less OBS architectures

The contentions are the main reason why OBS networks are not preferred. The disadvantage of the contention resolution approaches [6] is that they increase control and architecture complexity due to necessity of additional systems, e.g., wavelength converters, fiber delay line (FDL), to be installed. Therefore, after some time of stagnation in the research in the field of OBS networks a new trend started to be seen, i.e., Loss-less OBS.

The objective of loss-less OBS networks is to allow no loss. In other words, loss-less is only possible if there is a way how to mitigate contentions. Contentions can be mitigated, but under some price. The price of loss-less depends on the proposed architecture. The price can be seen as increased end-to-end delay, lower wavelength efficiency, etc.

1.3.1 CAROBS

Car-OBS (CAROBS) is a research project defined by Coutelen in his dissertation thesis [7], [8]. The aim of CAROBS is to create a robust, asynchronous, and all-optical mesh network. The robustness and efficiency is achieved with a new transmission mechanism called *burst train* which allows grooming in the optical domain and loss-less mode of operation due to contention resolution using electrical buffering.

CAROBS is a relatively controversy framework because it is labelled as all-optical framework, but uses electrical buffering. Buffering is a very promising approach of contention resolution in OBS [9], but for the time being, electrical buffering is the only method of buffering for a variable time in optical network currently because purely optical memories are not ready for commercial deployment and FDLs are space inefficient.

The node architecture defined by CAROBS framework unifies OBS Core and Edge into one CAROBS node architecture which serves both purposes. The unified architecture is beneficial because only this way an edge node can sense traffic, i.e., flows, between ports. This is very important for collision avoidance [10]. The CAROBS node architecture is captured in Figure 3. The Figure 3

contains visualisation of burst train, cars, traffic aggregation and disaggregation, and logical process of buffering into media access control (MAC) block that maintains scheduled burst trains in its internal memory. The CAROBS node architecture depicted in Figure 3 contains horizontal lines representing the input and output ports. Additionally, the ports are labelled with λ to emphasize different wavelengths. The λ_1 represents the wavelength reserved for the control channel and λ_x represents the wavelengths used for optical transmission. In Fig. 3, one can see that the CAROBS node architecture spans three logical layers, with the control plane on the top containing an *SOA Manager* that reads CAROBS header packet (CHP) and determines further node actions. According to the CHP's content, the CAROBS node can: a) switch a whole burst train; b) groom-out a first burst and switch the rest; c) buffer contending cars to the electrical memory. In order to do this, the *SOA Manager* creates a set of instructions for the Switching matrix (MX), then forwards the CHP to the next node on the dedicated wavelength λ_1. The central part is the electrical domain, and it is used for both the aggregation and disaggregation of user traffic as well as buffering contending burst trains in the MAC block. The bottom layer strictly resides in the optical domain. This layer is analogue only and represents the optical domain, where all cars are switched, and contains the MX block that switches the optical signal. If contention occurs, the contending burst trains are switched to the dedicated port for electrical buffering. These ports are directly connected to O/E blocks which convert optical signals to the electrical domain.
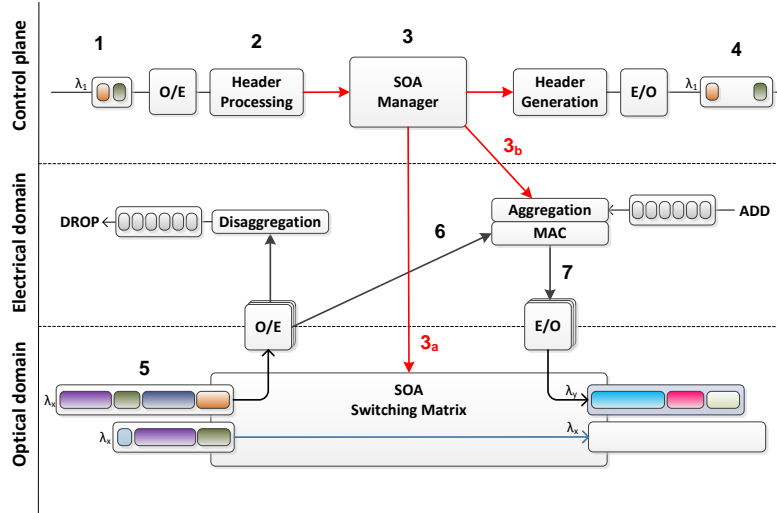

Figure 3: The CAROBS node resolves burst contention using an electrical buffer. The contending burst train is sent to the MAC and stored until the output port and wavelength are available again.

1.3.2 Buffering

The main devise of CAROBS framework is contention resolution tackled by buffering in electrical domain. Several concepts using electrical memory for contention resolution have already been proposed [11], [12], but these concepts are too complex. The unique CAROBS node architecture allows sharing most of electronic resources necessary for electronic edge and the buffering in core part of a network. The buffering in the core part of the network starts when a new burst train is about to arrive, the CHP arrives to CAROBS node **1** in advance and on a dedicated wavelength. Subsequently, the CAROBS header undergoes optical detection (O/E) where the optical signal is adjusted and equalized. Following this, the control data are prepared for control processor **2**. Control processor **3** verifies the time span needed for the reservation of the burst train. In case of contention, the requested time span overlaps with already-scheduled burst trains, therefore, the SOA manager instructs MX and MAC **3a,b** to buffer the contending burst train. The SOA manager uses one instruction for MAC to set the buffering delay d_b, and two instructions for MX – buffering and unbuffering. These two instructions are assigned to MX with respect to the OT and just-enough-time (JET) signal protocol,

so MX activates the configurations in $OT - d_s$ and $OT + d_b - d_s$ respectively.

This efficient process allows the CAROBS framework to ensure zero burst loss. However, the CAROBS framework breaks the original OBS paradigm [4] and increases the delay in the optical segment of the network. Yet the CAROBS framework increases performance considerably [8] and provides the loss-less mode which is the central reason to adapt it further.

2   Aims of the doctoral thesis

This dissertation thesis deals with the limits of loss-less OBS networks. There are two related areas that need to be verified. It is the i) transmission ii) control of a loss-less OBS network. Specifically, the targets of this dissertation thesis are:

1. Analysis of loss-less OBS traffic properties, and definition of the working conditions under which the selected loss-less OBS framework can be used. Discussion the impact of loss-less OBS traffic properties onto the loss-less OBS viability.

2. Address the viability of loss-less OBS architecture and optimizations of loss-less OBS networks.

3. Formulate the optimization mechanism of the selected loss-less OBS architecture and show the maximal performance of it.

4. Define a control mechanism which is usable for OBS architecture and compatible with current technology. The proposed control mechanism must easily integrate into currently maintained networks. Also, this control mechanism must allow delivering the maximal network performance.

5. Implement simulations model using an event driven simulator in order to have a tool for verification of studies of the loss-less OBS networks.

3   Working methods and selected results

3.1   Traffic properties

The routing and wavelength assignment (RWA) tackles the problem of optical network dimensioning in terms of allocating bandwidth onto specific wavelength while holding optical network constraints. This means capacity of wavelength can not be over assigned by requested capacity of flows for every link in network, maximum of requested traffic must be transported, all the traffic must be link disjoint at one wavelength (OCS), traffic can be merged electronically (OCS), or etc. Very deep review of routing in OBS network was carried out by Klinkowsky *et al.* [6]. Klinkowsky *et al.* reviewed around 40 research papers dealing with RWA, categorized them according to their properties (Class, Routing type, Route selection, Features), route calculation approach, and suggested an optimization formulation based on linear program (LP) considering $M/M/k/k$ model.

This is very traditional approach, but it is very unfortunate because this approach does not consider Stream-line effect (SLE) [13]. Additionally, the CAROBS brings few features that must be considered by RWA as well hence this section opens the problem of CAROBS RWA formulation with description of statistical properties of CAROBS traffic, and the following sections going to tackle the CAROBS RWA dimensioning perspective and related problems. The main focus of the following analysis are to use already given optical network as efficiently as possible.

3.1.1   Statistical properties of CAROBS traffic

The CAROBS architecture gives new traffic characteristics that are related to OBS traffic characteristics. The CAROBS framework uses buffering for contention resolution which means the buffered traffic must be restored when it is possible. However, this un-buffering can cause contentions which are called *secondary contention*. The secondary contention occurs when a burst train is scheduled to

be un-buffered 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 arriving burst train is buffered. This means neither the $M/M/k/k$, nor the SLE model work for buffered OBS exclusively. Secondary contention was studied by Delesques *et al.* [14] using the Engset model. Their main concern was the buffer size dimensioning, so they defined buffering probability (BP). BP is a comprehensive parameter of buffered OBS networks hence cannot be easily quantified by $M/M/k/k$ model, with respect to SLE. Therefore, the SLE model and secondary contention must be mutually evaluated.

The CAROBS traffic characteristics are closely bounded to the buffering process that has implications into the CAROBS node dimensioning problem. At the first glance, the optimization of the node architecture might seem to be easy using the Erlang C formula. The Erlang C formula gives burst blocking probability (BBP) that seems to be equal to the BP. However, there are two perennial shortcomings: the Erlang C formula only works for systems with buffering before the service [15]. Moreover, the contenting burst cannot be buffered unless there are enough O/E blocks. It means that there are servers, which need to be optimized, before the buffering can be optimized. Therefore, for the purpose of further discussion the CAROBS node architecture must be reformulated using the tools of Queueing theory [15]. Such a redefinition is vital because it allows separation of two optimization problems a) the buffering problem itself b) optimization of the number of O/E blocks. Due to this separation these two problems can be tackled individually.

3.1.2 Buffering process quantification

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 analysis, an approximation model relying on simulations, prior to the design of a mathematical model in the future, is discussed. The main focus is on the basic node behaviour under various conditions, using the topology described in Figure 4. The most important node, the node under study, is marked as merging node v, see Figure 4. There is also destination node d where all traffic flows, from sources $s_\bullet$, are destined. The number of sources changes, so four scenarios with 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 [16]. Simulations were carried out using OMNeT++ simulator and CAROBS models [17]. Source nodes $s_\bullet$ were supplied with traffic generated according to the 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 [4] was used as a signalling protocol and Latest available unused channel with void-filling (LAUC-VF) algorithm [18] for burst assembly.
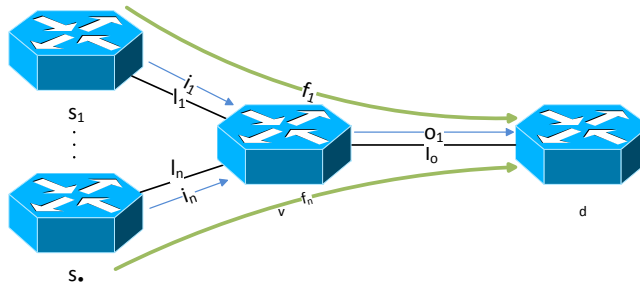

Figure 4: The elementary topology used for one node behaviour evaluation. The number of sources was changed as is depicted here by $s_1, s_2, \ldots, s_\bullet$.

In these simulations, 25 identical simulations are carried out 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 $BP(\alpha, MF)$ and buffering delay $BD(\alpha, MF)$ 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 $1/(MF + 1)$ 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. With regard to this approach, there must be enough data for the proper statistical evaluation, hence, valid interpretations.

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. In this experiment the number of wavelengths $|\Lambda|$ is changed from 1 up to 60.

3.1.3 Results

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 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 dependence of the coefficient $K(|\Lambda|)$, which addresses the stationary level of node, is illustrated in Figure 5.
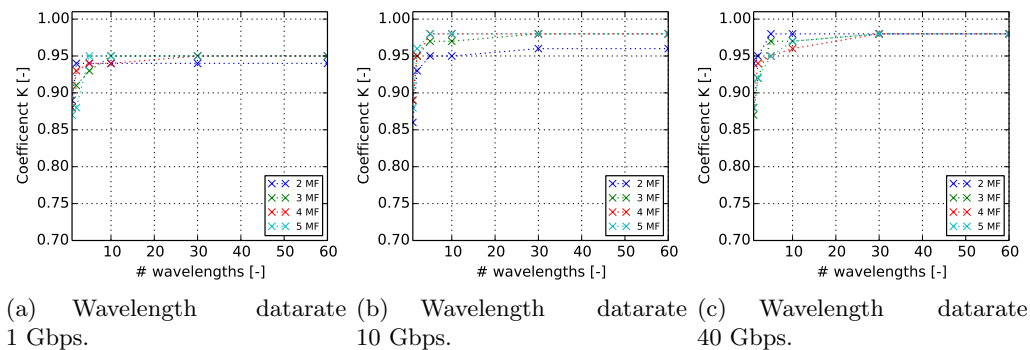

(a) Wavelength datarate 1 Gbps.

(b) Wavelength datarate 10 Gbps.

(c) Wavelength datarate 40 Gbps.

Figure 5: 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.

The inclination of coefficient $K(|\Lambda|)$ to the value one is seen, however, in the studied range of wavelengths the coefficient $K(|\Lambda|)$ does not meet it. It results into the gap of bandwidth F_{BW} that cannot be used for static traffic but could be used for frequently bursting short term flows which cannot result in excessive buffering. The graphs of Buffering delay (BD) and BP are depicted in Figure 6. BP is captured for two and five MF in Figure 6abc), $\mathrm{BD}(\alpha, |\Lambda|)$ is depicted in Figure 6def) without respect to the number of MF, because of the Poisson character of merging flows. Both BP and BD improved significantly as the number of wavelengths $|\Lambda|$ increased. It is an excellent indicator that further research on O/E block sharing 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 and it can be used to minimize the number of deployed O/E blocks in the network. The objective can be formulated as the minimization of MF and maximization of the stream lining. In this section, it is obvious that SLE is highly important for the CAROBS node and its performance.

The number of O/E relates to BP, and the graphs are depicted in Figure 7(a). The one-wavelength scenario is captured here to depict the upper bound. One 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 for designing simple CAROBS nodes with minimal requirements. On the other hand, it allows to design CAROBS nodes which tackle most contention.

3.2 Implications to the design of CAROBS GRWA algorithm

In order to find a routing an grooming routing and wavelength assignment (GRWA) algorithm must be properly formulated. The main focus is the capital expenditure (CAPEX) and operating expense
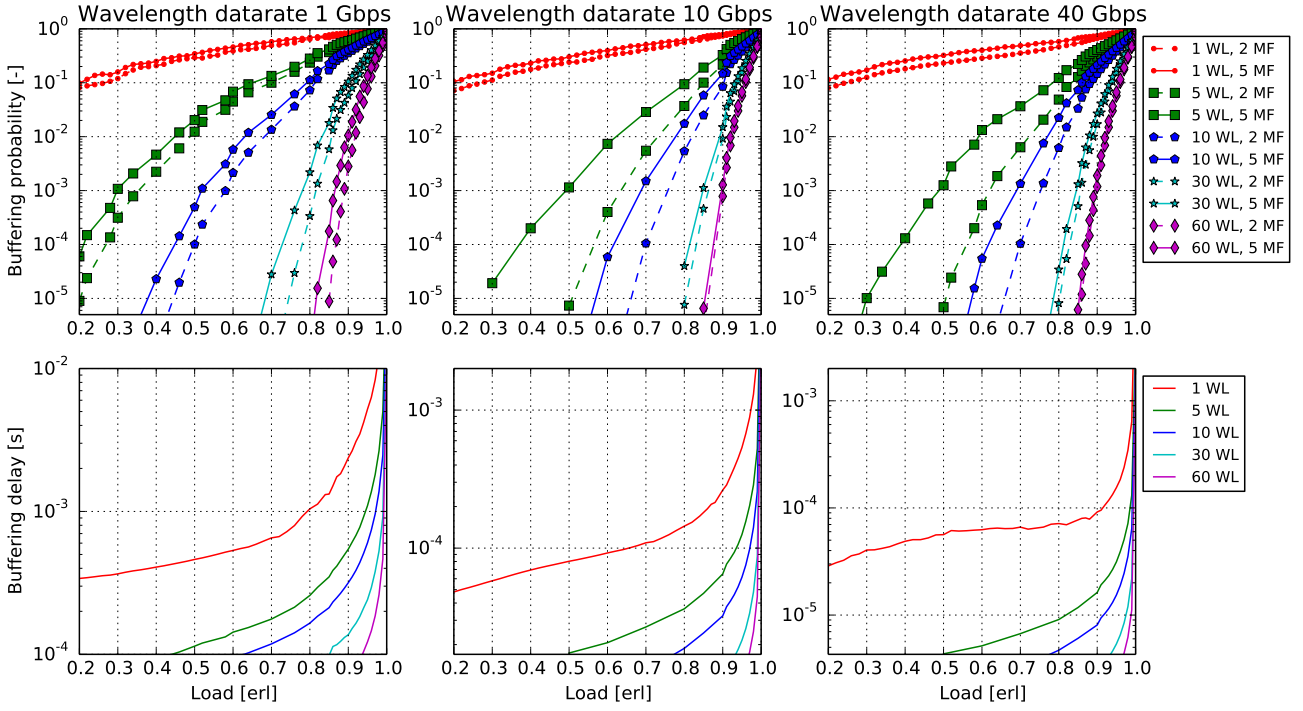
Figure 6: A comparison of CAROBS using the WDM system. The upper set of figures depict the buffering probability for six different wavelength sets and two and five MF. The lower set of figures captures the average buffering delay with no respect to the number of MF. Both sets offer clear evidence for shared O/E blocks deployment.

(OPEX) minimization hence the installation of O/E blocks must be minimized. The CAPEX and OPEX minimization is tightly bounded to results captured in Figure 7(a). These results can be used as sum of all O/E blocks across nodes in a network. However, these results are very hard to use because they have non-linear nature. It means with a small change of the Load they do not change linearly which is necessary for linear programming formulation that is selected for optimizations in this thesis. Therefore, the linearisation is necessary, and the linearised results are depicted in Figure 7(b). The price for linearisation is in the accuracy of results hence the non-linear lines were approximated with a line that gives minimum error.

When the parameter describing dependence of the number of O/E blocks on the Load is linearised, the number of O/E blocks can be calculated using the (1) for $x > b_{thresh}$. The b_{thresh} represents the node load when some contentions can occur, so O/E blocks are necessary.

$$\overline{O/E} = b_0 + b_1 x \tag{1}$$

At this point extra attention must be paid because the linearised data are normalized to the number of wavelengths $|\Lambda|$ in the WDM transmission system. Therefore, the accurate number of O/E blocks is function of Load, the number of wavelengths $|\Lambda|$, and most importantly to the number of merging flows MF. The total number of O/E blocks per one node can be enumerated as (2).

$$O/E(\Lambda, \alpha, MF) = |\Lambda| . \left(b_{0,|\Lambda|,MF} + b_{1,|\Lambda|,MF} \alpha \right) \tag{2}$$

The dependence of the number of O/E blocks is caused by the dependence of parameters b_0, b_1 to the number of wavelengths and merging flows. This dependence of b_x parameters is captured in the Figure 7.

Objective function

Objective function determines the main scope of optimization algorithm, so the (3) contains two parts which are balanced using penalties PENAL$_{xxx}$. The preference of the solution can be formulated

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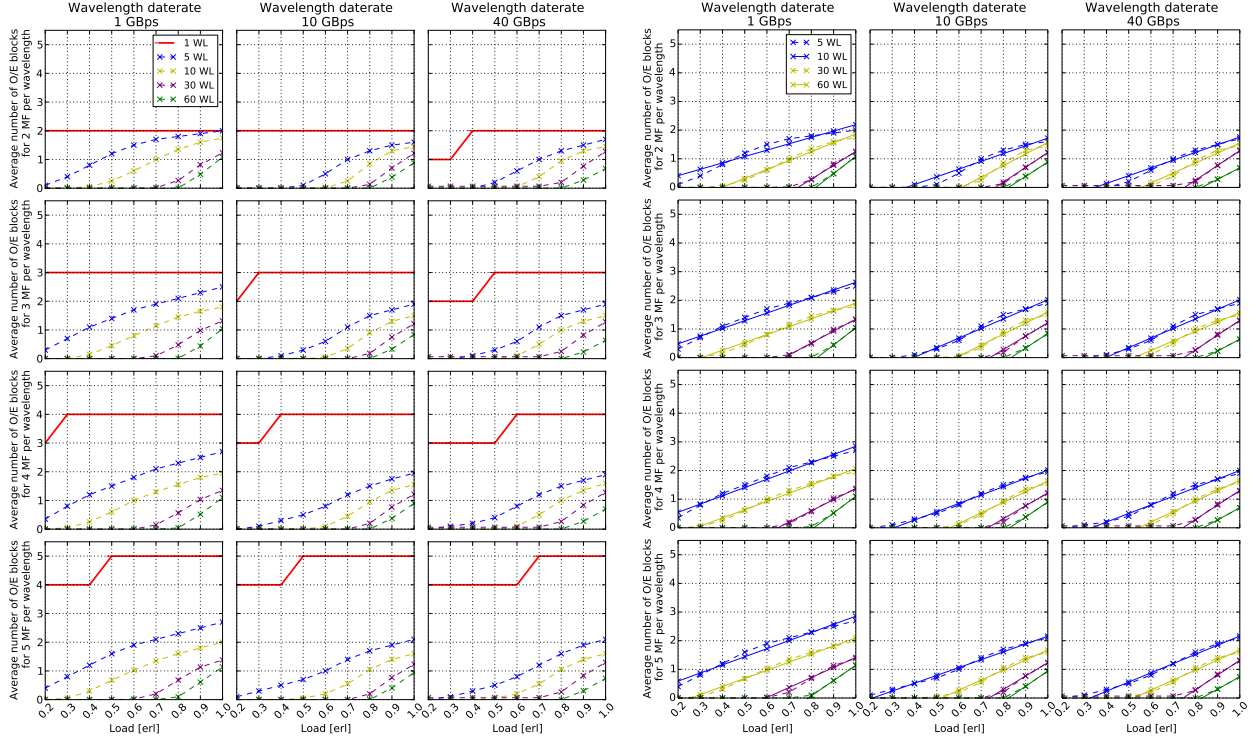
(a) Estimation of the average number of O/E blocks per wavelength with respect to the egress port load. The higher the number of wavelengths shared by one O/E block, the lower the total number of O/E blocks. The upper boundary for the system containing a higher number of wavelengths is lowered because it is over the threshold K, i.e., a load that should not be reached.

(b) Linearized function of the average number of O/E blocks
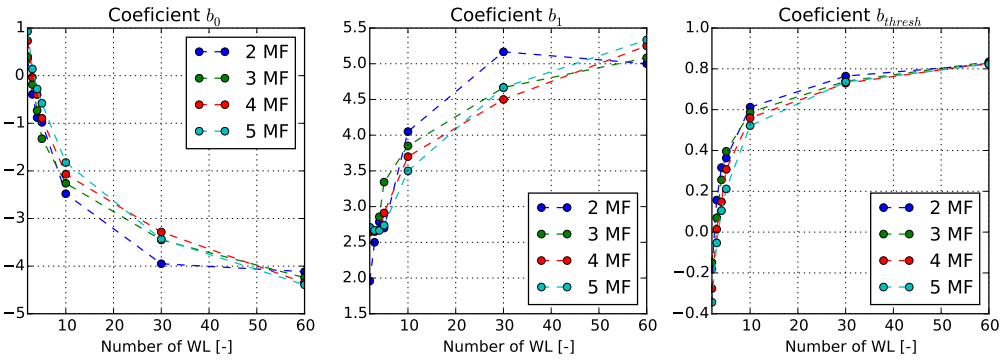
Figure 7: Values of b parameters with respect to the number of wavelengths, at 10 Gbps per wavelength.

towards to the either unsupported traffic PENAL_D or network cost PENAL_OE. Eitherway, each solution of the integer linear program (ILP) program highly depends on the requested traffic D and physical properties of the optical network, such as Λ and network topology which can be represented as a graph $G(\mathcal{V}, \mathcal{L})$. The objective function is formulated as follows:

$$\min \left(\text{PENAL}_\text{D} \sum_{(s,d) \in V^2 : s \neq d} e_{sd} + \text{PENAL}_\text{OE} \sum_{v \in V} OE_v \right) \tag{3}$$

where e_{sd} is a variable representing how much of traffic could not be routed because there is not enough wavelengths in Λ in order to support all traffic D.

9

Constraints: Flow-control

The crucial set of constrains is based on the Maximization throughput problem formulation that is extended with respect to the WDM. Therefore, the traffic RWA is captured by constrains:

$$\sum_{\ell \in \omega^+(v)} \phi_{\ell,\lambda}^{sd} - \sum_{\ell \in \omega^-(v)} \phi_{\ell,\lambda}^{sd} = \begin{cases} b_\lambda^{sd} & \text{if } v = s \\ -b_\lambda^{sd} & \text{if } v = d \\ 0 & \text{otherwise} \end{cases} \qquad v, s, d \in \mathcal{V}, \lambda \in \Lambda \tag{4}$$

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

$$\sum_{\lambda \in \Lambda} b_\lambda^{sd} = D_{sd} - e_{sd} \qquad s, d \in \mathcal{V} \tag{5}$$

$$\sum_{\lambda \in \Lambda} \sum_{s,d \in \mathcal{V}} \phi_{\ell_o,\lambda}^{sd} \leq |\Lambda|.C.K, \qquad \ell_o \in \omega^+(v), v \in \mathcal{V} \tag{6}$$

$$\sum_{s,d \in \mathcal{V}} \phi_{\ell,\lambda}^{sd} \leq C, \qquad \ell \in \mathcal{L}, \lambda \in \Lambda \tag{7}$$

$$\phi_{\ell,\lambda}^{sd} \leq y_{\ell,\lambda}^{sd} D_{sd}, \qquad \ell \in \mathcal{L}, \lambda \in \Lambda, s, d \in \mathcal{V} \tag{8}$$

where the $\phi_{\ell,\lambda}^{sd}$ is a non-negative variable representing the amount of traffic that is routed $s \to d$ at a specific wavelength λ, and the variable $y_{\ell,\lambda}^{sd}$ is the binary representation of variable $\phi_{\ell,\lambda}^{sd}$. The variable $y_{\ell,\lambda}^{sd}$ is one when $\phi_{\ell,\lambda}^{sd}$ is positive. The constrains (6) represent the maximal node load when the node is still stable. The constraints (5) are closely related to (4), and these constraints ensure maximization of routed traffic for each $s \to d$ request. The (7) restrict the maximal usage of each wavelength, and constraints (8) create the relation between variables $\phi_{\ell,\lambda}^{sd}$ and $y_{\ell,\lambda}^{sd}$. These variables are very important in order to mitigate minor routing problems related to loops, but for the sake of simplicity these constraints are not listed here.

Constraints: O/E counting

The Figure 7(b) and (2) give information how to enumerate the number of O/E blocks based on the node load, number of wavelengths $|\Lambda|_\ell$, and the number of merging flows MF_{ℓ_o}. In the previous section, the traffic routing is carried out, so an traffic routing framework is ready, and O/E blocks constraints are necessary in order to influence the flow-control.

Optical cross connect configuration

The configuration of the elementary MX reflects the RWA, i.e., how flows are routed. Each flow relates to a node v by variable $\chi_{v,\ell_i,\ell_o}^{sd}$ which is one when there is a sd flow at node v, connected from input port ℓ_i to output port ℓ_o, and at wavelength λ. Because the CAROBS enables traffic grooming, $\chi_{v,\ell_i,\ell_o}^{sd}$ variables can not be used for merging flows counting directly.

The values of variables $\chi_{v,\ell_i,\ell_o}^{sd}$ are derived from the decision variable $y_{\ell,\lambda}^{sd}$ using the following formulation:

$$\chi_{\ell_i,\ell_o}^{sd,\lambda} = y_{\ell_i,\lambda}^{sd} y_{\ell_o,\lambda}^{sd} \qquad v \in V \setminus \{s, d\}, \ell_i \in \omega^-(v), \ell_o \in \omega^+(v) \tag{9}$$

which puts into relation the input and output port at specific wavelength. The drawback of these constrains is, these constraints are non-linear hence they are not possible to use in ILP and must be linearised. The linearised formulation is as follows:
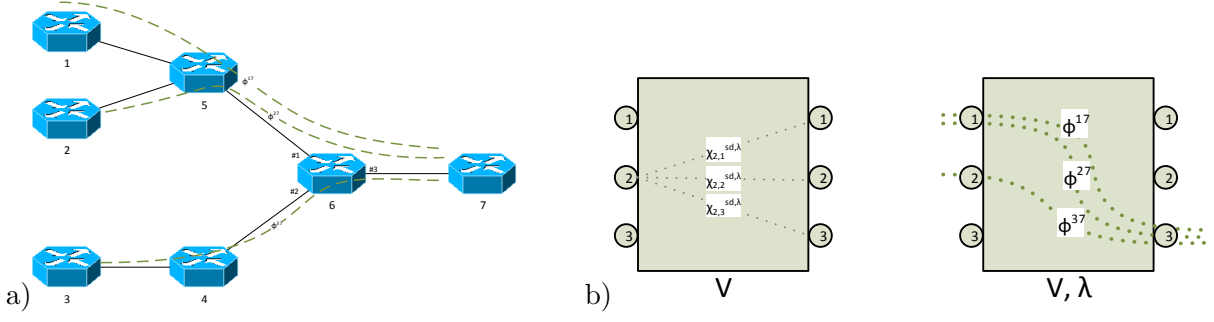
Figure 8: Visualisation of merging problem a) is the macro view and b) is the inside look at node **6**. Here, three flows are pictured all in the same colour (to underpin they are on the same wavelength) labelled by ϕ^{sd}. Most importantly, these flows correspond to the decision variables $\chi^{sd}_{v,\ell_i,\ell_o}$. This variable is one if such a connection is used by a flow ϕ^{sd} and zero otherwise. In the b), the decision variable $\chi^{sd}_{v,\ell_i,\ell_o}$ is depicted only for input port 4 in order to increase the figure readability.

$$\chi^{sd,\lambda}_{\ell_i,\ell_o} \le y^{sd}_{\ell_i,\lambda} \qquad v \in V \setminus \{s,d\}, \ell_i \in \omega^-(v), \ell_o \in \omega^+(v) \tag{10}$$

$$\chi^{sd,\lambda}_{\ell_i,\ell_o} \le y^{sd}_{\ell_o,\lambda} \qquad v \in V \setminus \{s,d\}, \ell_i \in \omega^-(v), \ell_o \in \omega^+(v) \tag{11}$$

$$\chi^{sd,\lambda}_{\ell_i,\ell_o} \ge y^{sd}_{\ell_i,\lambda} + y^{sd}_{\ell_o,\lambda} - 1 \qquad v \in V \setminus \{s,d\} \tag{12}$$

Merging flows calculation

The number of merging flows implicates the number of O/E blocks for every particular output port ℓ_o. The CAROBS uses sub-wavelength scheduling, so the variables $\chi^{sd}_{v,\ell_i,\ell_o}$ are problematic. For example, the situation in Figure 8 would result into 2 O/E blocks because there are two flows entering the node through port 1 and one flow entering node through port 2, and all flows are leaving the node by port 3. However, in this particular case only one O/E block is necessary. Therefore, a new variable $\xi^{\lambda}_{\ell_i,\ell_o}$ representing stream-lined flows is introduced. The variable $\xi^{\lambda}_{\ell_i,\ell_o}$ is one when there is at least one flow entering node through port ℓ_i and leaving through port ℓ_o at wavelength λ.
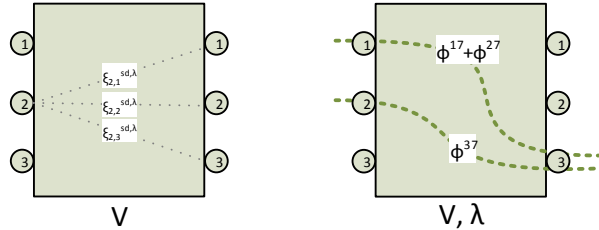
Figure 9: Visualisation of the MX configuration captured by $\xi^{\lambda}_{\ell_i,\ell_o}$. The flows Φ^{sd} are considered as merged compared to Figure 8.

The conversion of flow variables $\chi^{sd,\lambda}_{\ell_i,\ell_o}$ into stream variables $\xi^{\lambda}_{\ell_i,\ell_o}$ is realised by the big-M [19] notation bellow:

$$\sum_{\substack{sd \in V \\ sd \in \mathcal{V} \setminus \{v\}^2}} \chi^{sd,\lambda}_{\ell_i,\ell_o} \le \xi^{\lambda}_{\ell_i,\ell_o} M \qquad v \in \mathcal{V}, \ell_o \in \omega^+(v), \ell_i \in \omega^-(v) \tag{13}$$

$$\sum_{\ell_i \in \omega^-(v)} \xi^{\lambda}_{\ell_i,\ell_o} \le MF^{\lambda}_{\ell_o} + 1 \qquad v \in \mathcal{V}, \ell_o \in \omega^+(v) \tag{14}$$

The constraints (14) allow to count the number of merging flows, and the results is stored in the variable MF^{λ}_{ℓ}.

The number of wavelengths calculation

The next step on the way to find all parameters is to find the number of wavelengths participating in the contention. This is very similar approach to the MF enumeration (14). In the first step the indication of contention at wavelength λ must be obtained. In order to do that the big-M approach is used again:

$$MF_{\ell_o}^\lambda = w_{\ell_o}^\lambda M \qquad v \in V, \ell_o \in \omega^+(v) \tag{15}$$

$$\sum_{\lambda \in \Lambda} w_{\ell_o}^\lambda = W_{\ell_o} \qquad v \in V, \ell_o \in \omega^+(v) \tag{16}$$

In the second step the number of wavelength is enumerated for the output port ℓ_o.

The supplied bandwidth enumeration

All nodes in network are stable due to the constraints (6), so the total output port load can be obtained by simple sum of supported bandwidth routed through each output port ℓ_o:

$$\sum_{s,d \in V} \phi_{\ell_o}^{sd} = \alpha_{\ell_o} \qquad v \in V, \ell_o \in \omega^+(v) \tag{17}$$

O/E blocks calculation

The very last step is to calculate the number of necessary O/E blocks in order to deliver loss-less mode of operation using the (2). At this point, all informations were gathered together – (14), (16), (17). The (2) is then written as:

$$W_{\ell_o}.b_{0,W_{\ell_o}} + b_{1,W_{\ell_o}}.\alpha_{\ell_o} \leq OE_{\ell_o} \qquad v \in V, \ell_o \in \omega^+(v), \text{if } \alpha_{\ell_o} > b_{thresh,W_{\ell_o}}, \forall b_0, b_1 \tag{18}$$

$$\sum_{\ell_o \in \omega^+(v)} OE_{\ell_o} \leq OE_v \qquad v \in V \tag{19}$$

This formulation uses very same approach where there are dedicated variables bounded to one output port and values of these variables are summed together for each node v.

Parameters and variables:

In order to keep the mathematical model consistent the variables are defined here:

$$\phi_\ell^{sd} \geq 0, e_{sd} \geq 0 \qquad\qquad \{s,d\} \in V, \ell \in L \tag{20}$$

$$y_{\ell,\lambda}^{sd}, \xi_{\ell_o}^\lambda, w_{\ell_o}^\lambda \in \{0,1\} \qquad\qquad \{s,d\} \in V, \lambda \in \Lambda, \ell \in L. \tag{21}$$

$$MF_{\ell_o}^\lambda, W_{\ell_o}, OE_{\ell_o}, OE_v \in \mathbb{N}^0 \qquad\qquad v \in V, \ell_o \in \omega^+(v) \tag{22}$$

$$\alpha_{\ell_o} \geq 0 \qquad\qquad v \in V, \ell_o \in \omega^+(v) \tag{23}$$

As one can see, this ILP program relies on some variables, but considerable part of them has many parameters which makes the solution very difficult. More parameters a variable has increases the size of the variable that is represented by a matrix for the solution using the Simplex algorithm.

3.3 Stream-line effect based RWA

The special case of the CAROBS GRWA is to define a routing such that no flows are merging, i.e., RWA based SLE. The ILP formulation of SLE-RWA is designed to maximize the traffic D_{sd} deployment in a given network $G(\mathcal{V}, \mathcal{L})$. The objective function of the ILP SLE-RWA is to minimize amount of unsupported traffic U_{sd} between each node pair $(v_s, v_d) \in \mathcal{SD}$:

$$\min \sum_{(v_s,v_d) \in \mathcal{SD}} U_{sd}. \tag{24}$$

This objective function is subject to two set of constraints that a) tackle the traffic routing b) ensure no merging flows in the network. The first set of constraints of ILP SLE-RWA focuses on the traffic routing in the network. The ILP SLE-RWA allows to groom more traffic flows onto the same wavelength if the wavelength capacity B is not exceeded. The un-supported traffic U_{sd} is calculated using constraints (26).

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

$$v \in V, (v_s, v_d) \in \mathcal{SD} \tag{25}$$

$$D_{sd} = \sum_{\lambda \in \Lambda} b_\lambda^{sd} + U_{sd} \qquad (v_s, v_d) \in \mathcal{SD} \tag{26}$$

$$\sum_{(v_s,v_d) \in \mathcal{SD}} \varphi_{\ell,\lambda}^{sd} \leq B \qquad \ell \in L, \lambda \in \lambda. \tag{27}$$

Every request D_{sd} is routed by one flow-path at each wavelength. Additionally, the ILP SLE-RWA formulation tackles loops at intermediate nodes, so efficient usage of links in the network can be achieved: For $\lambda \in \lambda, (v_s, v_d) \in \mathcal{SD}$,

$$b_{\min} y_{\ell,\lambda}^{sd} \leq \varphi_{\ell,\lambda}^{sd} \leq D_{sd}\, y_{\ell,\lambda}^{sd} \qquad \ell \in L \tag{28}$$

$$\sum_{\ell \in \omega^+(v)} y_{\ell,\lambda}^{sd} \leq 1; \ \sum_{\ell \in \omega^-(v)} y_{\ell,\lambda}^{sd} \leq 1 \qquad v \notin \{v_s, v_d\} \tag{29}$$

$$\sum_{\ell \in \omega^-(v_s)} y_{\ell,\lambda}^{sd} = \sum_{\ell \in \omega^+(v_d)} y_{\ell,\lambda}^{sd} = 0 \tag{30}$$

$$\sum_{\ell \in \omega^+(v_s)} y_{\ell,\lambda}^{sd} = \sum_{\ell \in \omega^-(v_d)} y_{\ell,\lambda}^{sd} \leq 1. \tag{31}$$

The SLE is ensured in the network by following set of constraints:

$$y_{\ell_i,\ell_o,\lambda} \geq y_{\ell_i,\lambda}^{sd} + y_{\ell_o,\lambda}^{sd} - 1 \qquad \lambda \in \lambda, (v_s, v_d) \in \mathcal{SD}, v \in V \setminus \{v_s, v_d\}$$
$$\ell_i, \ell_o \in L : \text{DST}(\ell_i) = \text{SRC}(\ell_o) = \{v\} \tag{32}$$

$$\sum_{\ell_i \in L:\text{DST}(\ell_i)=\text{SRC}(\ell_o)} y_{\ell_i,\ell_o,\lambda} \leq 1 \ \ell_o \in L, \lambda \in \Lambda, \tag{33}$$

which express the wavelength connectivity at each node $v \in \mathcal{V}$. Every wavelength connectivity is captured by the variable $y_{\ell_i,\ell_o,\lambda}$ which is one only if there is at least one $(v_s, v_d) \in \mathcal{SD}$ flow going from input port connected to link ℓ_i to output port connected to link ℓ_o, routed on wavelength λ. The difficulty to solve the routing for the ILP SLE-RWA comes from the huge number of variables that are necessary:

$$y_{\ell,\lambda}^{sd} \in \{0,1\} \qquad \ell \in L, (v_s, v_d) \in \mathcal{SD}, \lambda \in \Lambda \tag{34}$$

$$y_{\ell_i,\ell_o,\lambda} \in \{0,1\} \qquad \ell_i, \ell_o \in L : \text{DST}(\ell_i) = \text{SRC}(\ell_o), \lambda \in \Lambda \tag{35}$$

$$\varphi_{\ell\lambda}^{sd} \geq 0 \qquad \ell \in L, \lambda \in \Lambda, (v_s, v_d) \in \mathcal{SD} \tag{36}$$

$$b_\lambda^{sd} \geq 0 \qquad \lambda \in \Lambda, (v_s, v_d) \in \mathcal{SD} \tag{37}$$

$$U_{sd} \geq 0 \qquad \{s, d\} \in \mathcal{SD}. \tag{38}$$

Most variables are indexed by wavelength λ, but their value is nonzero for only one wavelength λ. This characteristic of the ILP SLE-RWA model generates scalability issues even for small networks with

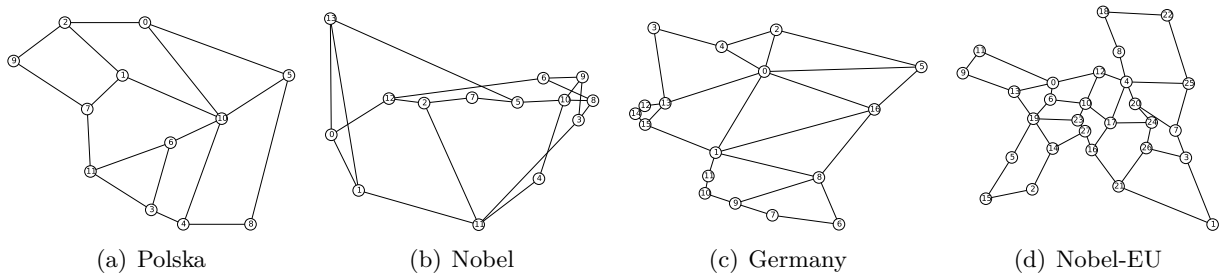(a) Polska   (b) Nobel   (c) Germany   (d) Nobel-EU

Figure 10: Network topologies used for analysis, taken from SNDlib [21]

a large number of wavelengths. Using a decomposition model allows solving each set of constraints for one generic wavelength as an independent ILP program, consequently with significantly less variables. In other words, using a decomposition model, one large complex problem is not solved, but a number of significantly less complicated and smaller problems [20] are solved.

3.3.1 Experiment Settings

The SLE-RWA optimization algorithm described in the previous section provides routing with no merging flows, but still with some contentions caused by the aggregations – secondary contention. Although, the buffering is seen beneficial in terms of burst loss avoidance, the buffering introduces extra delay to every buffered burst train. Generally, the buffering is a new term in all-optical networks; therefore, it is important to verify the impact of the traffic and network topology on CAROBS network performance in terms of SLE-RWA routing. For the purpose of this study, the CAROBS network performance is quantified by BBP, access delay (ACC), end to end delay (E2E), and BD. These performance parameters describe CAROBS nodes in time domain and reflect the network behaviour from an ISP perspective.

In order to verify the CAROBS network performance, tests were run on four network topologies depicted in Figure 3.3.1. These topologies come from SNDlib [21]; however, since the traffic D_{sd} provided by SNDlib was not sufficient for the purpose of experiments, the D_{sd} was generated using random number generator based on uniform distribution.

Based on the routing obtained from SLE-RWA, 20 simulations were carried out to mitigate the impact of random number generator seed number used in the simulator for traffic generation. The simulations are run using OMNeT++ simulator and CAROBS models [17]. The source nodes s supply traffic generated according to a Poisson distribution to the CAROBS network in the simulation.

3.3.2 Simulation Results

The performance parameters for the four topologies of CAROBS networks are captured in Tab. 1. Values of performance parameters are calculated as a mean value over all nodes in the network where these performance parameters are measured. Information about confidence intervals are not provided because the values of Standard error are less than 5% of mean value hence providing such a small number would impair the table readability.

The simulations are carried out for traffic D_{sd} that SLE-RWA distributes on multiple wavelengths and flow-paths. In other words the network load is already given, so the load does not change in this analysis. The network load is quantified as *Average link utilization* and represents load offered to one outgoing link.

When one looks at the values of performance parameters of the Polska network, it is obvious that the buffering is applied onto nearly 25% of burst trains hence the average BD of each burst would be 0.062 ms. At the same time this 25% of burst trains require 116 O/E blocks in order to deliver loss-less mode for the traffic of 1.33 Tbps. This traffic is distributed into 7 wavelengths with the maximal efficiency of one wavelength is 86%. Basically, wavelength utilization higher than 30% is very appealing and very difficult to achieve for OCS systems, i.e., any system without all-optical grooming.

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Topology		Polska	Nobel US	Germany	Nobel EU
Burst buffering probability	[-]	0.242	0.069	0.068	0.094
Access delay	[ms]	0.022	0.025	0.049	0.061
Buffering delay	[ms]	0.257	0.211	0.252	0.272
End-to-end delay	[ms]	0.642	0.329	0.368	0.476
# wavelengths	[-]	7	9	16	56
Configuration utilization:					
Maximum	[%]	86.12	71.12	73.52	93.13
Average	[%]	68.43	48.49	48.27	44.36
Average link utilization	[%]	72.52	56.84	58.15	56.87
Average # of contenting flows	[%]	92.42	25.64	18.77	28.51
Requested traffic	[Tbps]	1.33	2.18	5.02	13.88
# flows	[-]	121	182	272	2256
Shortest paths	[%]	90.61	85.98	76.39	73.19
Nodes	[-]	12	14	17	28
Links	[-]	18	21	26	41
Diameter	[-]	4	3	6	8
Potential contentions	[-]	116	62	85	579
O/E blocks	[-]	36	60	65	305

Table 1: Performance

Even if the average link utilization would imply considerably higher BBP, BBP is very low for the other tested topologies. Such a low BBP is caused by the combination of multiple factors. First of all, the other networks contain more links and nodes, so the routing algorithm has more options where to route the traffic. Another monitored parameter is *Average number of contenting flows* that quantifies the amount of aggregations because the SLE routing avoids primary contention. This parameter should be read as a coefficient specifying how much of traffic is aggregated at a node in the network. At the same time, what is left over 100% corresponds to remaining capacity for bypass. Polska network exhibits inclination for aggregation. On the other hand, the remaining topologies have bypass inclination.

As one can see, the SLE-RWA algorithm works well with higher amounts of traffic. Higher amounts of traffic allow the algorithm to use more wavelengths. With more wavelengths, the algorithm can efficiently use the SLE. The SLE causes high link utilization and minimal contention. Most importantly this algorithm allows achieving very high wavelength utilization. The main drawback of this algorithm is the weak load balancing.

3.4 Software-defined networking and CAROBS networks

Although the CAROBS framework provides promising performance, it cannot be deployed in its current state as it does not define any management and control routines. For this reason, it has decided to study the control plane of the CAROBS framework. Future networks, including CAROBS, should provide a programming interface to provide flexible services based on a customer's immediate needs. The suggested software-defined networking (SDN) paradigm allows convenient network control and integration to ISP networks. Consequently, the CAROBS framework was extended to Software-defined CAROBS (SD-CAROBS) based on OpenFlow (OF) principles. SD-CAROBS is a more general concept describing the overall architecture, not only the network control mechanism.
The four main ideas of the SD-CAROBS are:

1. The SDN Controller and RWA evaluation is distributed and run in a virtual environment. The virtual environment is used to provide higher scalability, reliability, and CAPEX and OPEX savings.

2. One shared wavelength is dedicated to both control messages and the CAROBS header. This control wavelength is split into two subchannels and is present throughout the SD-CAROBS network.

3. The RWA evaluation is set aside in a separate compute layer. RWA algorithm results are used to generate optimal forwarding instructions and traffic classifiers for ingress nodes [8].

4. Forwarding instructions, i.e. a list of particular output ports along the selected flow-path, and traffic classifiers are uploaded only to the SD-CAROBS ingress nodes through control messages.

3.4.1 General architecture

The SD-CAROBS concept follows the SDN architecture [22], so the SD-CAROBS architecture contains an infrastructure layer, a controller layer. The complete architecture diagram is depicted in Fig. 11.
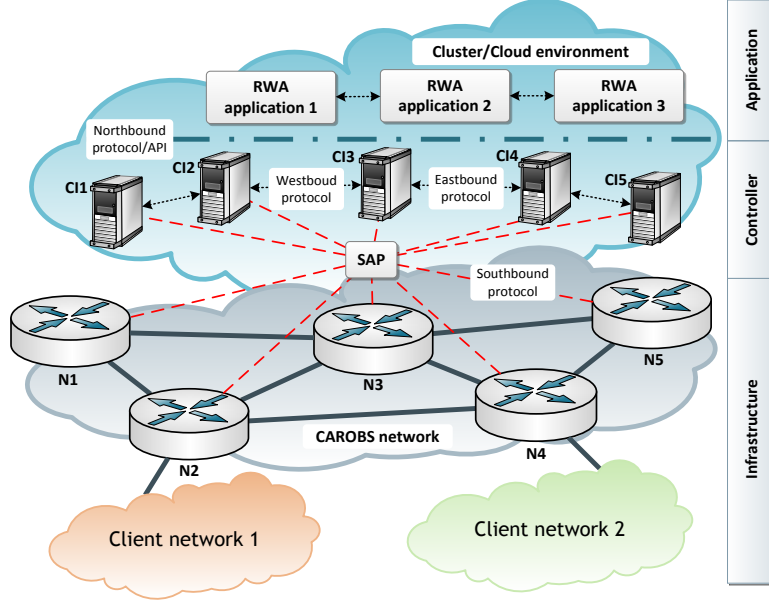

Figure 11: High-level view of SD-CAROBS architecture. Both client networks and SD-CAROBS nodes are placed on the base infrastructure layer. Nodes communicate with the controller by southbound protocol, via the Service Access Point (SAP). The logically centralized controller, compounded of more controller instances, and the RWA application in the distributed cooperation run on the higher layers. Inter-controller communication is realized via westbound/eastbound protocol, whereas the RWA application accesses the controller layer through a northbound API/protocol.

The application layer sits on the top, and it allows running various control applications, e.g., algorithms to solve the RWA problem in managed network. Running the RWA as an application is vital because it has been proven that RWA is an NP-complete problem [23]. Therefore, solving RWA at each SD-CAROBS node could be performance-demanding and time-consuming. Additionally, calculating the same problem at multiple SD-CAROBS nodes simultaneously would result in a number of duplicities in terms of obtaining the same RWA at multiple SD-CAROBS nodes. More importantly, each node would have to be equipped with high-performance computational resources to calculate a RWA algorithm, and this would increase the network OPEX. The necessity of compute resources could be reduced using heuristics; however, heuristics do not ensure an optimal solution, but heuristics may provide a sufficiently accurate RWA solution in acceptable time. The ISPs often have an extra computing capacity accessible through the Internet, so this surplus compute capacity can be used when running the RWA application.

The middle layer contains the logically centralized controller. The controller can be seen as a network operating system or a middleware between applications and network nodes creating infrastructure layer. The interface between the controller layer and the compute layer is defined solely by the controller implementation which usually includes a variety of REST and RESTful Application Programming Interface (API). Conversely, the interface between the controller and the infrastructure layer is limited to a few protocols available currently, e.g., OF. The node-controller communication is ensured by the TLS-secured TCP protocol on the transport layer. One node is usually connected to multiple instances of one logical controller, or, to multiple independent controllers in traditional SDN architecture.

The control network relies on the IP over Ethernet [24]. This combination is widely used today, and no extra work is required to establish communication in such a network. In order to avoid loops and broadcast storms, we suggest using the spanning tree protocols or its successor, the improved shortest path bridging protocol.

The bottom layer represents the underlying physical network, and this is called the infrastructure layer, see Fig. 11. The SD-CAROBS nodes operate on the infrastructure layer and they establish connections to the controller layer through the same physical network. The architecture of the SD-CAROBS node is depicted in Fig. 12, and the SD-CAROBS architecture is an extension of the original CAROBS node architecture as seen in Fig. 3. The new architecture adds an SDN layer represented by the SDN client and dedicated control channel. Each SD-CAROBS node is uniquely addressed according to the OF definition called the DataPath IDentifier (DPID). According to the OF specification, the lower 48 bits of DPID correspond to the node's MAC address and the upper 16 bits are left to the implementer. A total of 64 bits gives sufficient address space for an autonomous system run by an ISP.

Topologically, each SD-CAROBS node has a different functionality. The SD-CAROBS nodes can be located in the core or at the edge of the network. The main purpose of the edge nodes is to aggregate user traffic from adjacent locations. However, the edge nodes can switch burst trains from different edge nodes based on the corresponding SD-CAROBS headers. Even this burst train switching is core node behavior. This unified architecture can reduce network complexity, and also reduces burst contention [8] in the network. Every SD-CAROBS node is controlled from the upper layers as depicted in Fig. 12. The SD-CAROBS node is controlled via the SDN client which obtains instructions from the RWA application in the compute layer. Also, the SDN client collects statistical data from the SOA manager and forwards them to the RWA application on the compute layer. This information describe the flows based on the processed SD-CAROBS headers. To deliver all necessary statistical data, currently available OF statistics [25] need to be extended to account for buffered bursts, deferred bursts, memory utilization and buffering delay.
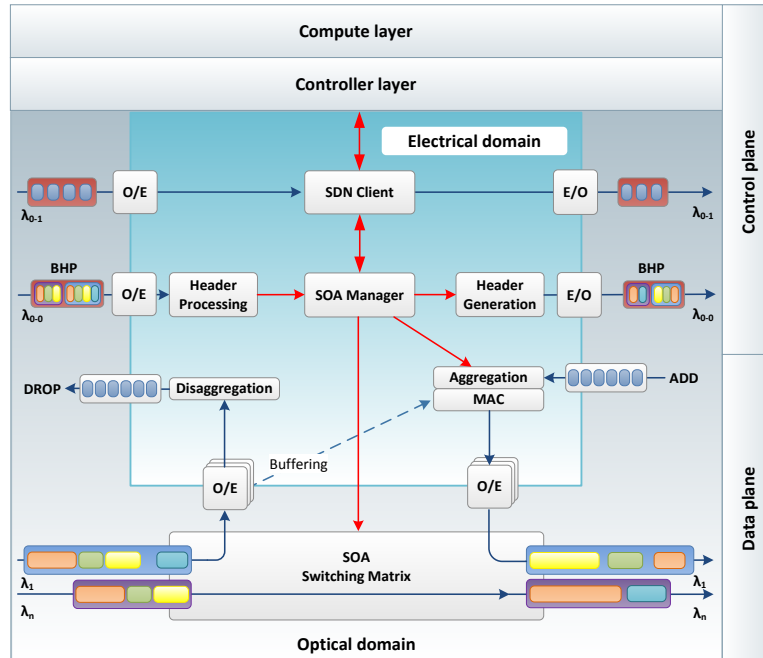

Figure 12: The SD-CAROBS node is split into an electrical and optical domain. All control messages and SD-CAROBS headers are converted by O/E and E/O converters. The node's architecture is the same for both Core and Edge nodes. The burst buffering process relies on the O/E block which converts deferred bursts into the node's electrical memory.

4 Conclusion

The viability of OBS networks is still a question, so I focused on the viability of the next generation iteration, i.e., loss-less OBS paradigm. Specifically, I worked with the loss-less OBS concept called CAROBS framework, and I further extended it by a new network control paradigm. I started the research with detail analysis of OBS networks, and this analysis led to the implementation of simulation models of the loss-less OBS framework CAROBS. Using these simulations models implemented in OMNeT++ event driven simulator, I carried out first experiment dealing with performance analysis of CAROBS networks [17], and I showed that deeper research is necessary.

Subsequently, I did an indepth analysis of the CAROBS network traffic behaviour, i.e., loss-less OBS network viability analysis. Results gave recommendation for using colour-less detectors and WDM systems with more than 10 wavelengths. This conclusion is compatible with the trend of optical networks today. Subsequently, the analysis allowed me to analytically formulate the CAPEX and OPEX. However, this formulation was very complex, so I could not use it for optimizations using the approach of mathematical programming, i.e., LP.

Consequently, I selected a corner case of this analytical formula. This corner case is based on the SLE approach, and it allowed to formulate GRWA using techniques of mathematical modelling. This formulation, however, is still too complex to be viable for bigger networks due to scalability, so I decided to use decomposition techniques in order to take advantage of the mathematical model structure. Specifically, I selected column generation (CG) approach then I created the CG reformulation of the original ILP formulation. The CG formulation is less accurate, but still provides optimal solution compared to some heuristics, i.e., still provides the best possible solution. This solution shows very appealing wavelength efficiency in mesh all-optical networking (AON) hence I showed that loss-less OBS architectures are viable.

This CG SLE-RWA formulations is still comprehensive, so traditional approach of its calculation is not possible to use. Nevertheless, calculation of SLE-RWA is pointless because SLE-RWA calculates routing strategy for whole network not for a particular node hence multiple same results would be gotten. Consequently, centralized control paradigm is designed. This proposed paradigm is called SD-CAROBS because it is based on the SDN approach for network control. Currently, the SDN is seen as future for the converged networks hence it is very good to define compatible network control because then it is easier to implement such an AON. Defining the SD-CAROBS, it is possible to control optical infrastructure and environement for services from one place hence more efficient use of all resources in ISP network can be achieved. In other words, SD-CAROBS allows to decrease ISP's CAPEX and OPEX.

Fulfilments of targets

All the goals that were set in Section 2 were **achieved**. Each goal's fulfillment is commented bellow:

1. **Analysis of loss-less OBS traffic properties and definition of the working conditions under which the selected loss-less OBS framework can be used. Discuss the impact of loss-less OBS traffic properties onto the loss-less OBS viability.**

   OMNeT++ models and computer clusters[2], so the results are statistically valid. Additionally, in order to find the CAROBS node stability threshold, I used the MVA analysis. Then I found the stability threshold, and the its dependence on the number of merging flows.

   Most importantly I quantified the dependence of the number of O/E blocks, so I showed the relation between the number of O/E blocks, the node load, number of merging flows, and number of wavelengths that implicates the CAROBS node price which results in CAPEX and OPEX of whole CAROBS network.

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[2]Used clusters: Metacentrum, Briaree, Mammouth parallèle 2, Mammouth série 2, and Guillimin that are part of Calcul Quebec. Simulations took around 13.000 Central Processing Unit (CPU) per day.

2. **Address the viability of loss-less OBS architecture and optimizations of loss-less OBS networks.**

   I synthesized the results of the previous target in the Section **??** and created the pillar for the formulation describing relation among the node load, number of wavelengths, and number of merging flows such that CAPEX and OPEX of a CAROBS network is possible to quantify.

   The most importantly, this formulation is formulated as an ILP program. However, this ILP program contains some non-linear constraints, so it is not possible to solve it using an solver, such as Cplex [26]. Therefore, the heuristics must be used in order to use this formulation, but the heuristics can be very inaccurate compared to ILP.

3. **Formulate the optimization mechanism of the selected loss-less OBS architecture and show the maximal performance of it.**

   The previous target showed the direction to follow in order to obtain an affordable CAROBS network. Therefore, I focused on the special case called SLE in order to exploit the CAROBS network performance. The SLE gives to create the RWA algorithm called SLE-RWA.

   In order to find the maximal performance, I modified this ILP to the form of a decomposition model because of the ILP model scalability issue. I decomposed the ILP into two ILP models which are closely related and together mimic the original ILP model, but scales. This model shows very high wavelength efficiency for all studied network topologies. Compared to well know OCS wavelength efficiencies, i.e., bellow 40%, the SLE-RWA allows achieving wavelength efficiency around 80%.

4. **Define a control mechanism which is usable for OBS architecture and compatible with current technology. The proposed control mechanism must easily integrate into currently maintained networks. Also, this control mechanism must allow delivering the maximal network performance**

   The current trend of network control tends to SDN which brings many appealing features, and the SDN tackles network traffic as flows which are very similar to flow-paths used for the CAROBS network traffic quantification. Therefore, it is very convenient to use SDN paradigm for CAROBS network control.

   The SD-CAROBS decouples RWA from node into a distributed environment, e.g., cloud services. Therefore, SLE-RWA can be used for RWA, so very high network, wavelength, efficiency can be achieved.

5. **Implement simulations model using an event driven simulator in order to have a tool for verification of studies of the loss-less OBS networks.**

   The loss-less OBS architectures are discussed as part of the section dealing with OBS network architectures that are provided in order to introduce a reader into the field of all-optical networks using the OBS paradigm. Based on the discussion of loss-less architectures the CAROBS architecture was selected. The simulation models were implemented using OMNeT++. OMNeT++ is becoming the standard because it is OpenSource and allows very versatile use. The implemented OMNeT++ models of CAROBS were first time published in [17].

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None

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Summary

The thesis deals with the problem of loss-less OBS paradigm viability for future all-optical networks. The viability problem is tackled from two perspectives. One perspective deals with the data transmission itself, and the second perspective deals with the network control. The research showed that the loss-less OBS paradigm can be improved from both perspectives.

The OBS networks are based on channel using statistical multiplex on the optical domain hence flows mixing occurs directly on the optical domain. Such a system can be classified analytically or empirically. The loss-less OBS architectures, however, are complex hence the empirical method was used in this thesis. Nevertheless, the empirical data which are created with a simulator can be used for analytical formulation of transmission behaviour. Simulation models capturing the selected loss-less OBS architecture were implemented, and the selected architecture was CAROBS framework. The CAROBS architecture is unique because allows buffering of contenting bursts in electronic domain. This buffering, however, degrades network performance parameters and increases CAPEX and OPEX. In order to find the relation between performance parameters and node load, an elementary node behaviour was studied using the CAROBS models implemented with OMNeT++ simulator. This experiment shows relation between node load and requirement of O/E blocks which cause increase of CAPEX and OPEX. Subsequently, the experiment shows that it is possible to define a routing strategy in CAROBS network in such a way that no O/E blocks are necessary in several nodes. This observation led to the formulation of an optimization algorithm which provides routing strategy such that minimum number of O/E blocks are used in a given network. The linear programming was selected because it can provide an optimal solution, but the formulation is not scalable due to the problem complexity. It means, the time to get results would not be proportional to the size of the optimized network. It is even possible that the optimization would try to solve the optimization formulation several days or weeks.

Heuristics were not used because a rigorous method is necessary in order to formulate a claim on the loss-less OBS viability. Therefore, a special case of this complex formulation was selected. In this special case flows are not merging, i.e., SLE, and based on this case an optimization algorithm called SLE-RWA was formulated and implemented. This routing strategy is then verified using OMNeT++ models, and it was showed that loss-less OBS can achieve considerably higher wavelength efficiency than what is possible with OCS networks. Therefore, this routing strategy outperforms OCS systems, and it is possible to claim that the viability of loss-less OBS architecture was proved.

Then, the focus was shifted towards to the OBS network control. Network control does not depend on loss-less properties, but the control proposed in this thesis is based on CAROBS and SDN, i.e., SD-CAROBS is defined. This network control concept uses logically centralized controller and redefined OF messages in order to deliver necessary information for CAROBS framework control. The SDN based control is vital because it allows unifying optical infrastructure and service control in an ISP network. Therefore, using SD-CAROBS control mechanism allows to control OBS network in a seamless way that is still not possible in OCS networks.

Résumé

Předložená disertační práce se zabývá problematikou bezeztrátových OBS sítí a jejich uplatnění v rámci optických sítí budoucnosti. Vhodnost OBS sítí je zhodnocena na dvou rovinách. V jedné rovině byly zhodnoceny přenosové vlastnosti a v druhé rovině bylo zhodnoceno řízení OBS sítí. Na obou rovinách byla navržena zlepšení, jenž jsou popsány v předložené disertační práci.

OBS sítě jsou postaveny na základech kanálu s časovým multiplexem, tedy dochází k míchání toků přímo na optické úrovni. Takovýto systém je možné hodnotit analyticky či empiricky. Vzhledem ke značné složitosti bezeztrátové architektury bylo v této práci přistoupeno k emperické metodě, jakožto prostředku, který umožní získat data vhodná pro analytický popis. S využitím nástroje OMNeT++ byly vytvořeny simulační modely, jenž popisují chování zvolené bezeztrátové architektury OBS sítí. Byla zvolena architektura CAROBS. CAROBS je speciální tím, že jako jediná umožňuje pozdržení kolidujících shluků v elektronické paměti a tím dokáže zabránit ztrátě shluku. Nevýhodou takovéhoto řešení je však pokles výkonnostních parametrů a navýšení nákladů na vybudování a provoz takovéto sítě. S využitím simulačních modelů bylo ověřeno chování prostého uzlu CAROBS sítě a byly určeny souvislosti mezi zatížením uzlu a výkonnostními parametry. Velmi důležitým závěrem bylo určení souvislosti závislosti počtu O/E bloků, jenž primárně ovlivňují cenu CAROBS sítě a zatížení uzlu. Závěr tohoto experimentu byl, že je možné definovat směrovací politiku v síti takovou, že na zvolených uzlech nejsou požadovány žádné dodatečné O/E bloky, jenž by zajišťovaly bezeztrátovost. Toto pozorování dále vedlo ke zformulování optimalizačního algoritmu, který umožňuje nastavit směrování v síti takovým způsobem, že je v síti instalováno minimum O/E bloků a zároveň bude zajištěn bezeztrátový provoz. Jako nástroj bylo využito matematického aparátu lineární programování. Navržený optimalizační předpis bohužel není možné použít pro rozsáhlé sítě, jelikož by jeho využití bylo výpočetně náročné a výsledky by nebylo možné získat v rozumném časovém horizontu.

Bylo by možné využít např. heuristických přístupů, avšak za cenu snížení přesnosti. Záměrem práce bylo podat přesné výsledky, a proto heuristická metoda nebyla využita. Aby bylo možné využít lineárního programování, byl zvolen speciální případ obecného optimalizačního předpisu. V případě, že nedochází k míchání provozu z více směrů nedochází ke srážkám shluků, tento případ je označován jako Stream-line efekt. Pro tento speciální případ byl připraven matematický model popisující směrování provozu v síti, tento model byl pojmenován SLE-RWA. Výsledky tohoto matematického modulu byly ověřeny pomocí simulačních modelů s využitím simulátoru OMNeT++. Ověření simulátorem prokázalo velmi dobré hodnoty přenosových parametrů, specificky byly prokázány velmi vysoké hodnoty efektivity využití kapacity vlnových délek v porovnání s dnes využívanými systémy postavenými na přepínání optických okruhů OCS. Proto si dovoluji tvrdit, že byla prokázána vhodnost bezeztrátových OBS sítí v prostředí optických sítí budoucnosti.

Následně byla pozornost věnována efektivnímu řízení OBS sítí. Obecně je dobré si uvědomit, že řízení nezávisí na schopnosti bezeztrátového přenosu, avšak navržený řídící mechanismus je navržen pro CAROBS architekturu a SDN přístup k řízení sítí. Navržený mechanismus řízení využívá logicky centralizovaného kontroleru a upravených zpráv protokolu OF. Zprávy byly upraveny tak, aby bylo možné předávat informace související s řízením provozu v CAROBS sítích. Využití SDN v řízení optické infrastruktury je příhodné, jelikož umožňuje sjednocení řízení běhového prostředí služeb s řízením vlastní přenosové infrastruktury v síti ISP. Navržením architektury SD-CAROBS jsem významně přispěl ke sjednocení řízení optické infrastruktury a prostředí pro služby zákazníků. Takovéto řízení dnes stále není možné v prostředí OCS sítí.