Improving RWA-OBS Formulation and Solution

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Abstract—**Loss-less transfers are commonly associated with circuit switching: Circuit switching in all-optical networks (OCS) prevent from collisions by avoiding multiplexing below the wavelength granularity. Spectral multiplexing can be combined with time multiplexing in opaque networks at the expense of additional equipment (MSPP) and complex synchronization issues. Optical Burst Switching has been proposed a decade ago as a promising alternative to OCS: Its asynchronous nature and its arbitrary granularity open the possibility of statistical multiplexing, but it is not well suited to handle loss-less requirements. Wavelength routing and TDM can still be performed at the expense of a slight modification of the control plane, but those solutions override the OBS flexibility and avoid the statistical multiplexing.**

The RWA-OBS problem tends to solve the drawbacks of both WR-OBS and SOBS. Based on several properties related to the in advance reservation and the data plane transparency of OBS, it integrates particular cases where two flows can be multiplexed on a given wavelength in a genuine OBS fashion without loss. We first enhance the original RWA-OBS formulation and then describe an iterative greedy heuristic and a column generation approach to improve the computing time and the scalability of the model. Experiments are conducted on two topologies to illustrate the potential of RWA-OBS that can compete with SOBS without requiring synchronization. The new proposed methods are then compared in terms of computing times and qualities. The efficiency of the column generation approach allows the integration of an additional constraint to control the compromise between the burst insertion delay and the throughput.

I. Introduction

The OBS popularity fluctuated since its emergence [1] a decade ago. The infatuation of this promising technology declined, mainly because of the difficulty to achieve loss-less transfers. In OBS, contentions can occur even under a light load and still today, no mechanism, either in space, time or spectral domain can ensure that all contentions can be solved [2]. Proactive mechanisms such as load balancing can reduce the contention rate (e.g., [3], [4]), but pure OBS loss-less configuration has not yet been achieved.

Polymorphous OBS (POBS, [5]) describes a slightly modified control plane that enables circuit switching at a wavelength (WR-OBS) and sub-wavelength (SOBS) granularity together with opportunistic transfers in a genuine OBS fashion. Circuit transfers can handle loss-less requirements but WR-OBS avoids statistical multiplexing and suffers from its coarse granularity (similarly to OCS, see [6]). Optical grooming can be achieved to reduce the granularity of WR-OBS (see, e.g., [7]). This technique is however not limited to WR-OBS and can be adapted to our proposal. SOBS solves the granularity issue by multiplexing several sub-wavelength connections in a TDM manner, but it introduces several complex synchronization issues (see, e.g., [8]–[10]). SOBS has been successfully applied in [11] where the authors restructure the network topology around a set of interconnected clusters.

Both WR-OBS and SOBS avoid loss by preventing contentions. In OBS networks however, the streamline effect [3] and the offset time priority [12] disclose particular cases where a burst is ensured to survive potential contentions. As a result, a kind of statistical multiplexing can be done asynchronously without loss.

The streamline effect emanates from the data plane transparency: The bursts are signaled in-advance by a header so that the switches can be configured before the burst arrival. It entails that the delay between two successive bursts remains unchanged as long as they use the same path. Consequently, as two bursts entering a given input port cannot overlap, they cannot contend for any output port (see [13]).

Contentions thus only occur between bursts arriving from different input ports and requesting the same output port for overlapping time periods. If available contention resolution mechanisms fail, only the first signaled burst will survive (regardless of its effective arrival date). What matters is the header arrival time, largely decided by the offset time (OT) assigned to the burst. The OT introduced by the JET reservation protocol [1] solves the lack of optical memory in the data plane: The header is responsible for resource reservation and is sent ahead of the payload so that it can be converted, processed and re-emitted in the optical domain before the burst arrival. The OT budget is spent while going through each intermediate node. As a result, the burst to be dropped (the latest signaled) is more likely to be the closest one to its destination (the one with the smallest OT). In [12] and [14], an extra offset time is used in order to achieve service differentiation. The mechanism performs isolation of bursts of a given priority over bursts of lower priority. Nevertheless, the mechanism only provides control on the flows that are affected by the loss but does not avoid loss.

Mutual isolation between two flows can be achieved by a careful use of the electrical buffering at the network entrance. The ALAP MAC protocol described in [15] ensures that an isolated transit burst survives a contention with an ingress burst. As the ingress burst is still in electrical domain, it also survives by accessing electrical buffering. The idea is to delay the ingress burst reservation as late as possible so

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that transit bursts header precedes the contention discovery. In some configurations disclosed in [15], the access delay is significantly increased, but the end-to-end delay is still reduced as then we rule out retransmission mechanisms.

The RWA-OBS problem was first introduced in [15] and performs routing and wavelength assignment. Contrary to RWA for OCS (see, e.g., [16]) or WR-OBS, ingress flows and transit flows can be merged if the transit flows are OT-isolated and the ingress nodes run ALAP. The streamline effect then avoids further contention between the bursts of those flows. As a result, the granted flows have loss-less guarantee.

In [15], it is shown that extending the OT improves the loss-less multiplexing potential and, consequently, the grade of service. The formulation described in [15], however, assumes a constant OT extension factor (EOT) for all flows. In this paper, we introduce the flexibility to use different EOT for each connection. To handle the model growth and improve its scalability we propose two solution mechanisms: A greedy heuristic and a column generation formulation combined with a Tabu search algorithm. Note that the ALAP burst insertion protocol can affect the delay. Our model integrates an additional set of constraints that controls the compromise between the delay and the throughput.

The paper is organized as follows. Section II presents the streamline effect, the offset based priority and the ALAP burst insertion protocol required for mutual isolation. Section III presents the isolation and mutual isolation patterns. Section IV describes our improved RWA-OBS model and a greedy heuristic. The column generation formulation is presented in Section V. Experiments are reported in Section VI. Conclusions are drawn in Section VII.

II. OBS PROPERTIES

A. Streamline Effect

The streamline effect relies on the observation that connections arriving on the same input port cannot contend. In the example illustrated in Figure 1, C_1 and C_3 can contend for the link $2 \rightarrow 3$, but the bursts that successfully access this link cannot contend for link $3 \rightarrow 4$, whatever the connection they belong to. Note the particular case of C_2 that merges with C_1 and C_3 on its first link. In that situation, electrical buffers can store bursts of C_2 to delay their emission and solve the contention.

The streamline effect is deeply investigated in [3], where the authors propose a reasonable approximation of the loss for multi-rate flows, as long as the number of sources remains small. Note that the Engset loss formula (see, e.g., [17]) also successfully reflects the streamline effect, whereas the Erlang-B loss formula should be rejected. These points are further discussed in [13].

B. Offset Time Priority

Contention occurs if a header requests an output port for a time slot that is not completely free. In the absence of contention resolution mechanism, the latest signaled burst is dropped. The offset time (OT) plays an important role in the

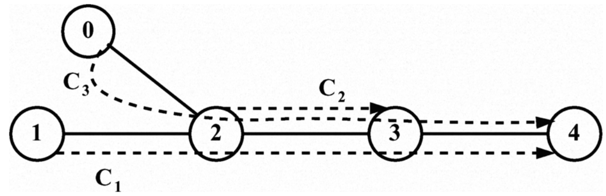

Fig. 1. contention

dropping process. In [15], a loss evaluation adjustment that takes into account the respective OT of the contending bursts is proposed. For the scope of this paper, we will only focus on the case where the OT protects a connection, i.e., the case where all dropped bursts belong to the same connection. It is illustrated by Figure 2. Burst B_1 is signaled by header H_1 at time t_1. Let us consider burst B_2 of duration b_2 signaled by header H_2 at time t_2 such that $OT_{B_1} - OT_{B_2} = b_2$. In that case, no contention can occur if H_2 arrives before H_1 (Figure 2-C). Indeed, in case of contention, H_2 necessarily arrives after H_1 and B_1 cannot be dropped. More formally, B_1 is dropped if the bursts contend and H_2 arrives before H_1, i.e., if $t_1 > t_2$ and $t_2 + OT_{B_2} + b_2 > t_1 + OT_{B_1}$. The two conditions can be rewritten as follows: $0 < t_1 - t_2 < b_2 - (OT_{B_1} - OT_{B_2})$ to highlight the fact that B_1 cannot be dropped if $OT_{B_1} - OT_{B_2}) > b_2$. Although the OT should depend on both the route and the class of service of the bursts, in this paper, we assume that all bursts traveling on a given route have the same OT, computed as follows:

$$OT_r = \delta \times \ell_r \times \alpha_r \quad (1)$$

where δ is the header processing time, ℓ_r is the number of hops on r and $\alpha_r \geq 1$ is an OT extension factor, used to increase the priority of the bursts on r (similarly to the extra offset time used in, e.g., [14], but in a multiplicative way). As a sequel, at a given node, B_1 is isolated from B_2 if $\ell_{r_1}\alpha_{r_1} - \ell_{r_2}\alpha_{r_2} > b_2/\delta$.

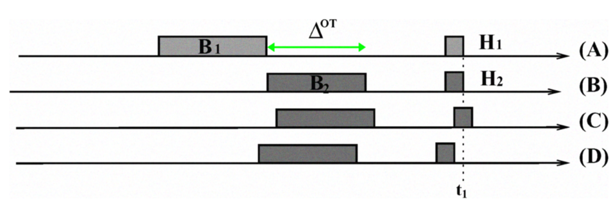

Fig. 2. OT priority

C. ALAP protocol

If a burst contends for its first link, it is still in electrical domain and can be stored in electrical buffers in order to survive from the contention. The electrical buffering, however, can increase the offset time of the ingress burst if not managed properly. A side-effect is that isolation state of transit flow may be broken. The ALAP protocol consists in delaying both the burst and the reservation attempt so that the OT of the

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ingress burst is not perturbed by electrical storage (see [13] for more details). Figure 3 illustrates the ALAP protocol, formally described by Algorithm 1.

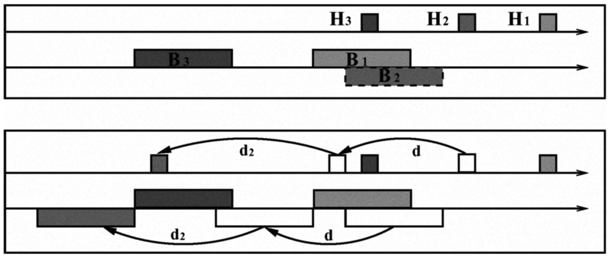

Fig. 3. The ALAP Burst Insertion

Burst B_2 is aggregated and ready to be launched at time t_2. The output port is requested from $t'_2 = t_2 + OT_{r_2}$ to $t'_2 + b_2$. As the output port has already been reserved by H_1 for an overlapping period of time, B_2 emission must be delayed in electrical buffers to solve the contention. The ALAP protocol consists in delaying the reservation attempts as well so that, in case of contention with further transit bursts, the ingress burst is the latest signaled and electrical buffering can be reused. In our example, the reservation for B_2 is postponed by d time units. This way, the ingress node keeps the control on OT_{r_2} and the isolation of B_3 is respected: H_3 arrives before the next reservation attempt of B_2 and B_3 can be served. This contention can be handled in the same way: B_2 reservation is postponed again by d_2 units of time and no burst is lost.

Algorithm 1 ALAP reservation protocol

Burst B of size b is ready at time t_{ready}
Compute OT; $t_{\text{res}} \leftarrow t_{\text{ready}}$; $t_{\text{send}} \leftarrow t_{\text{ready}} + OT$
repeat
  if at time t_{res}, resource is available on $[t_{\text{send}}, t_{\text{send}} + b]$ **then**
    reserve the resource
  else
    look for the next available interval $[t'_{\text{send}}, t'_{\text{send}} + b]$
    $t_{\text{send}} \leftarrow t'_{\text{send}}$; $t_{\text{res}} \leftarrow t_{\text{send}} - OT$; sleep until t_{res}
  end if
until reservation done.

The impact of the ALAP burst insertion protocol has been evaluated in [15]: The simulation involves a source of traffic whom bursts contend with transit bursts. The ingress node runs ALAP and the measured average insertion delay of ingress bursts is reported on Figure 4. The x-axis represents the proportion of ingress traffic in the overall load. The increase of insertion delay due to ALAP protocol is negligible if the ingress traffic dominates the transit traffic. Otherwise, the increase of the insertion delay remains reasonable for an overall load above 0.6 Erlang. By the way, the impact of the insertion delay must be compared with the end-to-end delay achieved with retransmission of the dropped bursts.

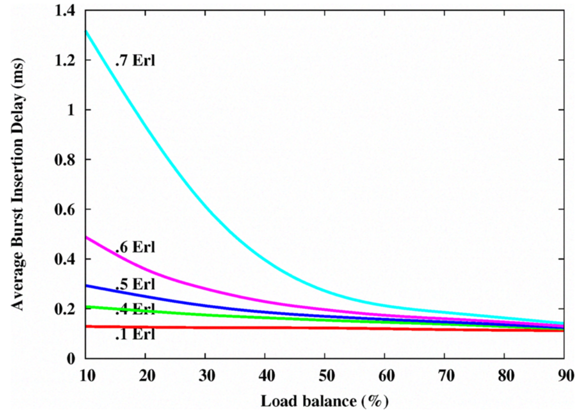

Fig. 4. Impact of ALAP on burst insertion delay

III. Flow Isolation

A. General Case

Route r is isolated from route r', denoted by $r \rhd r'$, if no burst of r can be lost due to bursts of r'. Thanks to the streamline effect, the isolation has only to be checked on the merging nodes (i.e., the nodes on which the routes converge). We have identified three isolation configurations. Firstly, link disjoint routes are isolated since they never converge. Secondly, a route is isolated on its first link as bursts can be stored in electrical buffers at their source nodes. Finally, the offset time priority discloses an additional isolation configuration as described in section II-B. We denote by $OT^v_{r_i}$ the remaining OT value of a burst on route r_i at node v. For given routes r_i and r_j, we define $\Delta^{OT}_{r_i,r_j} = \min_{v \in V}(OT^v_{r_i} - OT^v_{r_j})$, where V_{ij} is the set of nodes where routes r_i (carrying B_i) and r_j (carrying B_j) merge. By convention, $\Delta^{OT}_{r_i,r_j} = \infty$ if r_i and r_j are link-disjoint or if V_{ij} is reduced to the first node of r_i. $r \rhd r'$ if $\Delta^{OT}_{r,r'} > b_{r'}$, where $b_{r'}$ is the size of the bursts on route r'. Figure III-A illustrates this case. C_1 competes with C_2 at node 2. Destination of C_2 is more distant than the destination of C_1 so, without extra offset time, $\Delta^{OT}_{r_2,r_1} > 0$. If $\Delta^{OT}_{r_2,r_1} \geq b_1$, then $C_2 \rhd C_1$.

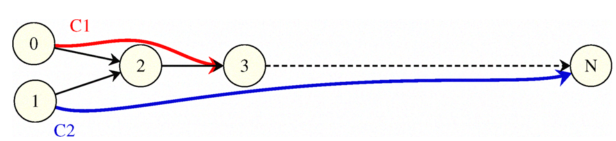

Fig. 5. General Isolation Case: Simple Bus Topology

Note that if $\delta > b_1$, then $C_2 \rhd C_1$ if r_2 is at least one hop longer than r_1. This is the most favorable case for maximizing the multiplexing potential of RWA-OBS. Although this assumption has been suggested in [12], it is worth to discuss its relevance at the light of recent contributions.

Several arguments suggest the use of small bursts for the purpose of the aggregation delay, the contention resolution (the efficiency of the FDLs is improved with smaller bursts,

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see [18]) or the goodput of TCP connections. In [19], authors shows that spreading the incoming load among several burstifiers (i.e., burst aggregation queues) reduces the impact of the synchronized loss on the goodput of TCP sources, but it mandates to reduce the size of the bursts to avoid long burstification time.

Opposite arguments can be set forth. Indeed, longer bursts reduce the signaling overhead and intensify the traffic shaping. This contributes, in turn, to reduce the contention rate in the core network (see [15], [20]).

All those arguments apply in some specific contexts, but the following one is valid independently of the equipment or protocols: The guard time between successive bursts, required to reconfigure the switch, links the size of the bursts with the maximal wavelength utilization and thus imposes a lower bound on the size of the bursts. In [21], the header processing time δ is around $50\mu s$, whereas the reconfiguration time is evaluated around 50 ns in [22]. Thus, if $b = \delta$, the guard time is reduced to 0.1% of the burst size. With 10 Gbps ports, the burst size would be 0.5 Mbit (around 150 IP packets as mesured in [23]).

B. Mutual Isolation

Routes r and r' are mutually isolated, denoted by $r \diamond r'$, if $r \rhd r'$ and $r \lhd r'$ (the negation is denoted $r \bowtie r'$). In addition to disjoint routes, mutual isolation can be achieved between a route that benefits from offset time priority and a route that can reach electrical buffering: Bursts on the former route always "win" the contention whereas the contending ingress bursts are delayed in electrical buffers. It is required that the burst insertion is managed by the ALAP protocol to avoid illegitimate resource access of ingress bursts. Two routes that merge on their first links are also mutually isolated since both can access electrical buffers. Mutual isolation is illustrated on Figure III-B. C_1 and C_2 only contend on their first link and are thus isolated. Under the assumption that $\delta \geq b_{c_3}$, C_1 is isolated from C_3 if node 1 runs ALAP. On the other side, C_3 is protected on its first link. On that example, C_1 is mutually isolated with both C_2 and C_3 so that two requests can be served simultaneously (either C_1 and C_3 or C_1 and C_2). Note that if bursts of C_2 are assigned an extra offset time greater than the size of the bursts of C_3, then all three connections can be granted with loss less guarantee.

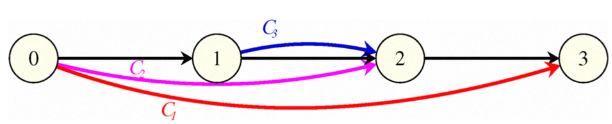

Fig. 6. Mutual Isolation

IV. RWA-OBS Formulation

A. Statement of the Problem

RWA-OBS is a provisioning problem. For a given traffic matrix, it aims to compute the routing configuration that maximizes either the number of granted requests or the overall amount of traffic granted so that for any two routes r and r' that carry flow, $r \diamond r'$. The RWA-OBS problem is lower-bounded (throughput wise) by the RWA problem used in WR-OBS or OCS (see, e.g., [16]) where $r \diamond r'$ if and only if r and r' are link disjoint. In synchronous networks (SOBS), it can be assumed that $r \diamond r'$ for any r and r' because the contention avoidance is performed by synchronization. As a result, RWA-OBS is upper bounded (throughput wise) by SOBS. Note however that SOBS requires synchronization management that can lead to a resource wastage that is not considered here.

B. Notations

Denote by F the set of flows, indexed by f. For a given f, let o_f and d_f be its origin and destination nodes, b_f its bandwidth. W is the set of wavelengths and Λ is the set of possible values for the OT extension factor. An OBS route r is associated with a wavelength λ_r and an OT extension factor α_r. In this section, x_r designates the flow carried by route r and $R^k_{f,\lambda,\alpha}$ is a set of k routes from o_f to d_f on wavelength λ with EOT factor α. We note R^k_f the union of all such sets related to connection f. L is the set of links and TC_ℓ is the transport capacity of wavelength w on ℓ. In opposition to the formulation proposed in [13], the OT extension factor is no more global, but associated with a route. As a result, two routes may have different extension factor. The number of OBS routes considered is thus $|W| \times |\Lambda| \times |F| \times k$.

C. ILP Model

$$z^{\text{OBJ}} = \max \sum_{f \in F} s_f b_f \qquad \text{subject to:}$$

$$U_{\ell,w} = \sum_{r \in R_w, p_r \ni \ell} b_{f(r)}\, x_r \leq \text{TC}_\ell \qquad \ell \in L, w \in W \tag{2}$$

$$x_r \leq y_r \qquad r \in R \tag{3}$$

$$y_r + y_{r'} \leq 1 \qquad r, r' \in R \,,\, r \bowtie r' \tag{4}$$

$$\sum_{r \in c\ell} y_r \leq 1 \qquad c\ell \in C\ell \tag{5}$$

$$\sum_{r \in R_f} x_r \geq s_f \qquad f \in F \tag{6}$$

$$x_r \in [0,1] \tag{7}$$

$$y_r \in \{0,1\} \tag{8}$$

$$s_f \in [0,1] \tag{9}$$

where x_r represents the fraction of flow $f(r)$ routed on route r. Variable y_r is linked to x_r by (3) so that y_r is equal to one if route r is used, zero otherwise. Constraints (6) set the variables s_f to the fraction of flow f served with loss-less guarantee. The capacity constraints (2) prevent the wavelength overload (we assume that all wavelengths of a fiber link have the same transport capacity). Constraints (4) prevent non isolated routes to be used simultaneously. Constraints (5) are added to strengthen the LP relaxation. We consider the so-called route conflict graph where each node is associated with

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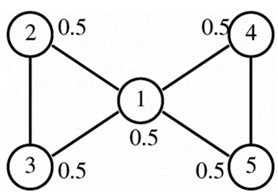
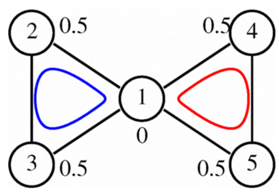
a route and two nodes are linked if their associated routes are not isolated. A clique $c\ell$ is a complete sub-graph (any two nodes of the sub-graph are connected). Let $C\ell$ be the set of all maximum (w.r.t. their number of nodes) cliques. The isolation constraints consists in allowing the use of no more than one route per clique. Figure 7 illustrates the improvement of the LP relaxation earned by the clique constraints (or cuts). Therein, the conflict graph exhibits two cliques. As a sequel, no more than two connections can be served, by using one route of each clique (2 or 3 and 4 or 5). In that example, route 1 should not be used since it belongs to both cliques. Without (5), the LP relaxation affects 0.5 to each route (Figure 7(a)) whereas constraints (5) avoid the assignment of flow on route 1 (Figure 7(b)).



(a) Formulation without (5)



(b) Formulation with (5)

Fig. 7. Isolation Formulation and LP Relaxation

Constraints (10) can be added to take into account the burst insertion delay with the ALAP protocol as discussed in Section II-C: A route can be used if the utilization of its first link is below a ceiling value $\tau \in [0, 1]$ (experiments suggest that $\tau = 0.6$ is conservative) or if the ingress flow has a major contribution on the load of the link.

$$y_r \leq (U_{r[1],\lambda_r} \leq 2b_f x_r) + (U_{r[1],\lambda_r} \leq \tau \mathrm{TC}_\ell) \quad r \in R \quad (10)$$

where $r[1]$ is the first link of route r.

D. Iterative Solution Algorithm

The number of routes considered directly impact the optimal value of the ILP model: Considering more paths and more EOT values improves the solution, but severely impacts the computing time. To sidestep large computing times, we propose an iterative greedy heuristic (IGH) that consists in iteratively increasing the set of paths (as described by Algorithm 2). At each iteration, one new route per flow is added in the model, the ILP model is solved starting from the solution of the previous iteration and the values of the variables related to the used routes are frozen. Note that the symmetrical nature of the ILP model can be broken by iterating the resolution along the wavelengths as well: Perform the iterative resolution on an increasing number of wavelengths.

After the last iteration, one can either release the values of all the variables and solve the ILP model (which means solve the initial ILP program with a good initial solution) or solve the ILP program only considering the routes that have been used at a given iteration.

Algorithm 2 Iterative Resolution of RWA-OBS

Compute R_f^k for each connection f.
repeat
  Insert a new route on λ into $R_{f,W'}$ for each flow f
  Solve RWA-OBS; Freeze and tag the used routes
until No route can be added OR all flows are served
Unfreeze all tagged routes
Freeze all untagged routes (suboptimal solution)
Solve RWA-OBS from the current solution

V. Column Generation Formulation

Algorithm 2 accommodates the scalability issue due to the number of paths. However, the RWA-OBS problem suffers from its symmetrical structure: There is a huge number of equivalent solutions, all deductible from each other using a wavelength permutation. It is known that integer linear programs (ILPs) with a huge number of equivalent solutions are getting quickly not scalable when, e.g., the number of wavelengths increases in the case of our study. However, turning to a large scale optimization formulation, there is a way to set a model where the number of solutions is greatly reduced, and not equivalent up to a some permutation.

A. Master Problem

In order to set such a model, let us define a RWA-OBS configuration as a set of routes that can be established on the same wavelength, i.e., that are OBS isolated from each other. Let $\mathcal{C}$ be the set of all possible configurations, indexed by $c \in \mathcal{C}$. Note that, for scalability reasons, the set R of considered routes will be limited to the first k shortest routes, for each pair of source and destination nodes with positive demand.

The model can be written as follows:

$$z^{\text{OBJ}} = \max \sum_{f \in F} s_f b_f + \epsilon \sum_{c \in C} \varphi_c \qquad \text{subject to:}$$

$$\sum_{c \in C} z_c \leq W \qquad (11)$$

$$s_f - \sum_{c \in C} \sum_{r \in R} f_r^c x_r^c \leq 0 \qquad f \in F \qquad (12)$$

$$\sum_{r} x_r^c f_r^c b_f = \varphi_c \qquad c \in C \qquad (13)$$

$$x_r^c \leq z_c \qquad c \in C, r \in R \qquad (14)$$

$$z_c \in \{0, 1\} \qquad c \in C \qquad (15)$$

$$s_f \in [0, 1] \qquad f \in F \qquad (16)$$

$$x_r^c \in [0, 1] \qquad r \in R \qquad (17)$$

where f_r^c is the maximum fraction of demand b_f served by route r, on configuration c. Denote by x_r^c the fraction of f_r^c actually activated and by s_f the fraction of the flow f that is accommodated, see constraints (12). Configuration c is activated if $\exists r$ such that $x_r^c \times f_r^c > 0$, see constraints (14). In that case, $z_c = 1$. As each configuration is activated on

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different wavelengths, the number of activated configurations must remain lower than W, see constraint (11).

B. Pricing Problem

The number of valid configurations is the number of cliques in the conflict graph. To accommodate this scalability problem, we will solve the LP relaxation of the master problem with a subset of configurations. Two solutions can be envisioned to build the subset: Either we proceed with an off-line enumeration of the configurations, or we generate them on-line. If we go ahead with off-line enumeration, only a subset of configurations can be generated, among the most promising ones, meaning we need a criterion to identify those. The on-line generation - that is the direction we will move along-rely on the use the column generation techniques to govern an efficient on-line configuration generation. The auxiliary problem (pricing) inserts a new configuration to the incumbent configuration set only if it improves the current value of the objective function, i.e., if it is a so-called augmented configuration. The pricing problem in charge of generating "augmented" configurations aims to maximize the sum of the reduced costs of connections and the objective can be written as follows:

$$\max \qquad -u_0 + \sum_f u_f s_f + \varepsilon(\sum_{f \in F} \sum_{r \in R_f} x_r b_f)$$

where u_0 and u_f are the dual variables respectively associated with constraints (11) and (12). The last term helps to add as much traffic as possible in the best configuration. For example, a route isolated from every route should appear in every configuration whether served or not.

The set of constraints is the same than in the original model described in Section IV, but the set of routes is restricted to a single wavelength (its cardinality thus decreases down to $|F| \times |\Lambda| \times k$).

$$x_r \leq y_r \qquad r \in R \qquad (18)$$

$$\sum_f \sum_{r \in R_f, r \ni \ell} b_f x_r \geq \text{TC}_\ell \qquad \ell \in L \qquad (19)$$

$$\sum_{r \in c\ell} y_r \leq 1 \qquad c\ell \in C\ell \qquad (20)$$

$$\sum_{r \in R_f} x_r = s_f \qquad f \in F \qquad (21)$$

$$s_f \in [0,1] \qquad f \in F \qquad (22)$$

$$y_r \in \{0,1\}, x_r \in [0,1] \qquad r \in R. \qquad (23)$$

C. ILP Solution

The column generation stops when the pricing problem cannot generate a column that improves the LP relaxation of the master problem. We next solve the ILP master, i.e., with z_c being 0-1 variables, with the current subset of configurations. Nevertheless, reaching the optimality of the LP relaxation does not ensure that the subset of configurations leads to the optimal solution of the MIP version of the problem. This phenomenon can be illustrated by Figure 7. Let us assume that routes 2 and 4 serve the flow f and routes 3 and 5 serve the flow f'. Only one wavelength is available. The optimal value is 2 for both the LP and ILP programs. An optimal LP solution is with configurations $c = [0, 1, 0, 1, 0]$ and $c' = [0, 0, 1, 0, 1]$ if $z_c = z_{c'} = 0.5$, whereas the ILP optimal value with this set of configurations is 1.

-	-	-	-	$z_a = 1$	$z_b = 1$
-	-	-	$z_a = 0$	$z_b = 1$	$z_c = 1$
...					
$z_a = 0$	$z_b = 0$	$z_c = 0$	$z_d = 0$	$z_e = 1$	$z_f = 1$
$z_b = 0$	$z_c = 0$	$z_d = 0$	$z_e = 0$	$z_f = 1$	$z_g = 1$

TABLE I
TABU ILLUSTRATION WITH 3 WAVELENGTHS

To force the LP master problem to stay with feasible integer solutions, we propose to freeze some configurations in the master problem to integer value. The management of the frozen configuration is done via a Tabu list. The size of the Tabu list is set to $2 \times |W|$. If the LP relaxation solution involves more than $|W|$ wavelengths, then the configuration c that handles the highest amount of traffic is added to the Tabu list and z_c is set to 1. The content of the Tabu list is swapped. The $W - 1$ earliest inserted configurations are frozen as used whereas the $W + 1$ last inserted ones are frozen as unused until they are discarded from the Tabu list.

Table I illustrates the Tabu list management with $|W| = 3$. z_a and z_b are frozen as used configurations. When z_c is inserted, the Tabu list content is swapped and z_a is frozen as unused whereas z_c is frozen as used. z_a cannot be used until it is discarded from the Tabu list (at the insertion of z_g).

Algorithm 3 Column Generation Tuning

```
repeat
  Solve the master LP relaxation
  if number of used configurations > W then
    add the most useful configuration in the Tabu list
    Solve the master LP relaxation
  end if
  Solve the pricing problem
  Add the new configuration in the master problem
until Time limit exceeds
Release all configurations; Solve the master ILP problem
```

VI. EXPERIMENTAL RESULTS

In this section, we report numerical results obtained on the NSF network (14 nodes and 23 links) and the New Jersey LATA network (11 nodes 23 links) available on [24]. We assume $b < \delta$ as discussed in Section III. The load is equal between each pair of nodes and expressed as a ratio of the wavelength transport capacity (10 Gbps).

A. RWA-OBS vs. WR-OBS and SOBS

We first compare the normalized throughput of loss-less guaranteed traffic handled with RWA-OBS, WR-OBS and

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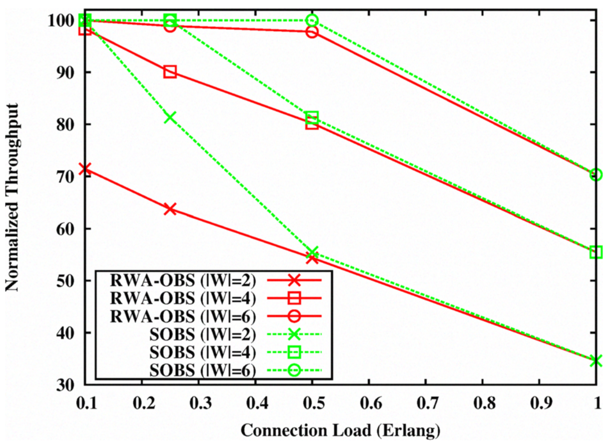
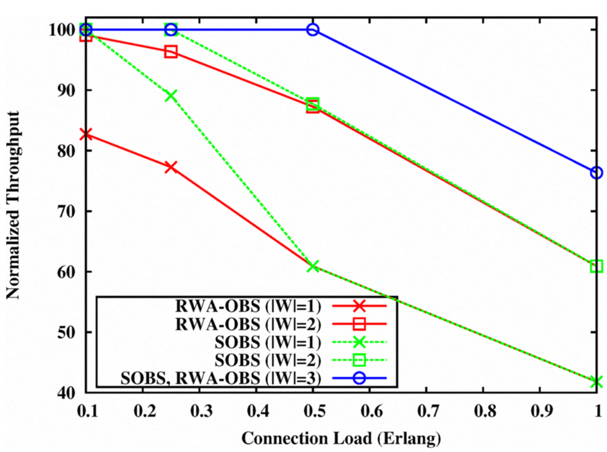
SOBS. In our experiments, we relaxed the synchronization constraints that can lead to resource wastage. The results thus reflect the best possible performance of SOBS.



(a) NSF Network



(b) New Jersey LATA Network

Fig. 8. Normalized Throughput

With WR-OBS, multiplexing is prohibited so that the throughput is equal to the throughput obtained with SOBS and RWA-OBS in the case where the load of each flow matches the wavelength transport capacity. With softer flows, multiplexing is possible with RWA-OBS and SOBS, so the normalized throughput increases and therefore, WR-OBS is outperformed. With SOBS, contention is avoided by external synchronization mechanisms so that any two flows can be multiplexed under the capacity constraint. The multiplexing potential of SOBS is thus maximum and the performances of RWA-OBS are in between those of WR-OBS and SOBS because the set of configurations that guarantee flow isolation is restricted to those identified in Section III. On the ring topology, the use of the OT extension factor elevates the throughput at the level of the one of SOBS. Figure 8(a) reports the results on the NSF network. SOBS outperforms RWA-OBS with soft connection load (10% of the wavelength granularity) and less than 4 wavelengths. However, if the load of the requests increases, the multiplexing potential of SOBS is reduced and the gap with RWA-OBS decreases: With request granularity of half the connection granularity, no more than 3% of the throughput is lost with RWA-OBS. The same observation can be done on the NJ-LATA network (Figure 8(b)): The gap between SOBS and RWA-OBS is negligible if connections request more than half the wavelength capacity, but increases when the connection load decreases.

B. Efficient Solution

The exact model presented in Section VI-A is heavy and requires large computation time. In this section, we compare the computation time and the quality of the solutions obtained with the iterative greedy heuristic (IGH) and the column generation approach (CG-RWA-OBS). Table II reports the computing times and the gaps between the heuristic values and the optimal values obtained with the ILP formulation. From the results, we can identify "easy instances" and "hard instances". Instances with a connection load of 0.5 Erlang are more difficult to solve because the symmetry of the problem is increased. If the load is equal to the wavelength transport capacity, then the wavelength capacity constraints prevent multiplexing and constraints (4) and (5) can be relaxed. On the opposite, the capacity constraints are useless if the load is equal to 0.1 Erlang. The instances with $W = 4$ are also difficult to solve because they are the largest instances where the full provisioning is impossible. The exact solution of the ILP formulation is highly dependent on the number of wavelengths. Indeed, the optimal solutions of the difficult instances could not be obtained in reasonable time. IGH clearly outperforms the ILP formulation in terms of computing times but the quality of the IGH solutions may not be satisfactory, especially for "hard instances" (with a 5% to 7.5% gap). CG-RWA-OBS improves the quality of the solutions, often up to the optimal solution. Computing times are comparable for easy instances and although computing times are longer for "hard instances", they remain reasonnable, especially when compared with those of the exact ILP model.

C. ALAP Delay Reduction

The addition of constraints (10) offers a control on the compromise between delay and throughput. As the model is significantly enlarged, we used CG-RWA-OBS to compute the routing tables on an instance with $|W| = 4$ and a request load of 2 Gbps. Table III reports simulation measurements of the throughput and the insertion delay for various values of the τ threshold parameter. As the threshold reduces the bandwidth availability, the grade of service of the RWA-OBS model is reduced for smaller values of τ. Consequently, the throughput as evaluated by simulation decreases, but the insertion delay is drastically reduced.

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	$\vert W\vert$	Load (Erlang)		
		0.1	0.5	1
ILP	2	36	> 2 weeks	1
	4	89,161	> 2 weeks	174
	6	5,274	> 2 weeks	6,820
	8	9,094	123,300	5,703
	10	20,133	106,531	8,236
IGH	2	3	458	1
	4	7	683	3
	6	22	6,628	5
	8	9	2,200	7
	10	12	752	19
$\text{Gap} = \frac{z^{\text{ILP}} - z^{\text{H}}}{z^{\text{ILP}}}$	2	2.4 %	5.0 %	0
	4	7.5 %	6.1 %	1.0 %
	6	0.6 %	5.1 %	0.8 %
	8	0	1.1	3.4 %
	10	0	0	3.1 %
CG - RWA OBS	2	6	24,290	1
	4	5,349	67,878	2
	6	319	76,822	2
	8	6	447	3
	10	6	56	3 , 223
$\text{Gap} = \frac{z^{\text{ILP}} - z^{\text{CG}}}{z^{\text{ILP}}}$	2	0	1.2 %	0
	4	1.2 %	0	0
	6	0.5 %	0	0
	8	0	1.1 %	0.75 %
	10	0	0	0.70 % , 0

TABLE II
SOLUTION SCHEME COMPARISON

Threshold (τ)	0.2	0.6	1
Throughput (Gbps)	226	256	286
Delay (ms)	0.15	1.0	1.7

TABLE III
BURST INSERTION DELAY REDUCTION

VII. CONCLUSION

In this paper, we have recalled the possibility of asynchronous loss less transfer with statistical multiplexing. The new RWA-OBS formulation improves on the first RWA-OBS formulation described in [15]: *(i)* The LP relaxation is improved by the clique constraints ; *(ii)* the OT extension factor can be tuned for each route so that the flexibility and consequently, the throughput is increased and *(iii)* an additional constraint is included to control the compromise between the grade of service and the burst insertion delay.

RWA-OBS offers an intermediate multiplexing potential between WR-OBS and SOBS but can achieve similar performances as SOBS if the request granularity is above half the wavelength transport capacity.

We proposed an iterative heuristic that can quickly provides acceptable solutions. The column generation approach, however, improves the quality of the solutions for a reasonable increase of the computing times. The flexibility of the column generation model allows for an easy addition of a constraint that effectively compromise between the burst insertion delay (increased by the ALAP burst insertion protocol) and the throughput.

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