A RWA Framework for Improved Throughput in OBS Networks

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Abstract— **All-Optical Burst Switched (OBS) backbone transport networks facilitate connectionless transport utilizing wavelength division multiplexing of multiple lightpaths end-to-end channels. The data in such networks is transmitted in the form of bursts. However, whereas such networks provide capacities in the Terahertz ranges, the data bursts being ferried often contend with each other at intermediate (interior) buffer-less nodes. The frequent occurrences of both contentions, as well as wavelength congestions, are often characterized by degradations in overall network performance in handling moderate to high traffic levels, and all this is attributed to increases in burst losses. Whereas deflection routing contention resolution is quite popular in combating both contention and wavelength congestions to improve overall network throughput, it is however necessary that network throughput always balances with effective utilization.**

Further complexity is that of most practical backbone transport networks often being multi-domain in nature and thus necessitating the dimensioning of deflection routing resources for both inter-domain and intra-domain traffic to avoid degradation of network performance in terms of contention as well as wavelength congestion occurrences in one domain due to improper dimensioning in the other(s). In this regard, a combination of appropriately designating border nodes and grooming interdomain traffic will vastly improve overall network performance as well as fairness to multiple domain lightpath connections.

In this paper, we propose a prioritized (indexed) cooperative-based routing and wavelength assignment (PIC-RWA) scheme that couples with wavelength grooming for inter-border traffic to reduce both contention and wavelength congestions. Performance results indicate that it significantly improves overall network performance in terms of improved effective resources utilization.

Index Terms— **deflection routing, contention, wavelength congestion, traffic grooming, border nodes.**

I. Introduction

Scalable Dense Wavelength Division Multiplexing (DWDM) based all-optical burst switched (OBS) networks have in recent years gained acceptance as a relatively cost-effective solution towards accommodating the ever-increasing bandwidth demands of network users. Typically, in such networks, the source-destination (S-D) pairs exchange data via all-optical lightpath channels. In practice, multiple domains are interconnected and hence a lightpath may span over several domains (Figure1). In general, a lightpath connection is assigned a unique wavelength end-to-end even though that may often result in wavelength continuity constraints, hence the use of wavelength converters (WCs) has been proposed even though that generally escalates both network capital as well as operational costs. The task of setting up lightpaths by routing and assigning a unique wavelength to every end-to-end lightpath connection is referred to as the RWA problem. Note that cost-effectively satisfying the wavelength continuity constraint will always result in fewer simultaneous connections being set up, and this is what mainly constitutes the core RWA problem. An alternative would be to increase the network resources to increases the number of simultaneous lightpath connections. In operational terms, since OBS utilizes one-way reservation, there is often no assurance that all transmitted bursts will reach their intended destinations [1].

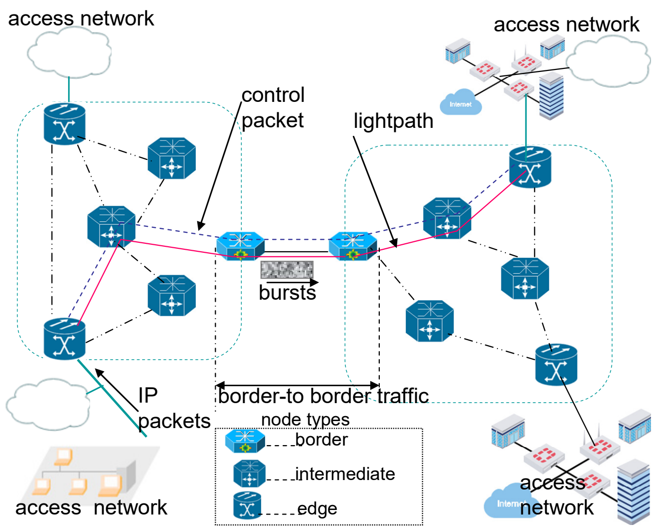


Fig. 1. An example multi-domain network

This is attributed to some lightpath connections being dropped at intermediate nodes due to both contentions as well as general wavelength congestion [1], [2]. Often, the burst blocking probability is used as a key performance measure in such networks. In practice, deflection routing can be implemented to alleviate both contention and wavelength congestion. However, in some cases, the bursts discarded at various intermediate nodes may have already utilized a substantial amount of network resources before the discarding, hence not contributing to effective network throughput. Whereas this may give a false impression of a rather high overall utilization, however, the end-to-end throughput would be considerably much lower. In any case, deflection routing also has several drawbacks, notably that it can accelerate contention as well as wavelength congestion on the deflection paths. Its performance is largely influenced by the general network topology and may not feature effectively where the numbers of candidate deflection paths are relatively small. In addition, it can also contribute to differential delays or jitter for successive bursts destined for the same receiver as the deflected bursts might either take a longer or shorter path than their non-deflected counterparts. It is thus imperative that the deflection routing itself be carefully implemented in a controlled manner.

II. RELATED WORKS

As indicated in the introductory section, the RWA problem constitutes simultaneously setting up end-to-end lightpaths across the optical backbone transport network as well as routing and assigning a unique wavelength to each lightpath connection setup. In so doing, the wavelength continuity constraint must be maintained, and at the same time, we thrive to maximize the number of simultaneous connections with minimal network resources possible. Once the network is operational, contentions will always occur in the intermediate nodes primarily because of their buffer-less nature. Extensive research work is focusing on minimizing the frequency of contention occurrence. The authors in [3] proposed and evaluated an algorithm that utilizes voids to minimize contentions as well as burst losses at subsequent nodes. The algorithm initially identifies all possible candidate void channels on which a data burst can be scheduled, before finally selecting one that maximizes the void utilization factor. Similarly, the authors in [4] propose a modified OBS paradigm that adapts assembled data burst sizes as a function of network traffic load. In this case, when network loads are high, longer data bursts are assembled by the ingress nodes. Triangular estimator-based burst scheduling algorithms are proposed in [5]. With these algorithms, all sections of the network that are currently prone to contention occurrences are identified as well as avoided when scheduling bursts. The authors in [6] studied the adverse effects of deflection routing load balancing on general TCP performance. In their work, they suggest source ordering as a means of improving TCP throughput performance. Based on earlier findings, the authors in [7] extended the work to proposing a Modified Horizon Scheduling algorithm with Minimum reOrdering Effects (MHS-MOE). Artificial intelligence-based techniques are utilized to enhance the network's routing decisions by the authors in [8] who propose and analyze a Reinforcement Learning-based Deflection Routing Algorithm (RLDRA). They aim to reduce data loss probabilities when the frequency of contention occurrences in the intermediate nodes becomes too frequent as a result of deflected data bursts. Their scheme tries to control the count of authorized deflections for each burst to reduce the extra traffic generated due to deflection contention routing being implemented. The scheme has a further advantage of reduced signaling as well as computational overheads.

A multi-class pre-emptive scheduling-based scheme on deflection paths (routes) is proposed in [8] in which an attempt is made to improve the general QoS of existing and future connections by implementing preemption policies on the onset of contention in any part of the network. The proposed scheme's complexity lies in the involvement of multitudes of parameters for determining and defining pre-emption probabilities and policies. Deflection Routing in an anycast-based OBS grid is proposed by the authors in [9]. However, the accompanying proposed enhanced deflection routing algorithm does not appear to address or alleviate the contention problem satisfactorily. Fairness and data burst loss owing to cascading constraints when bursts have longer hop count value in OBS networks is explored in [10]. The authors herein propose a preemptive scheduling technique for next-generation OBS networks in which newly arriving bursts with a higher priority may preempt already scheduled ones when contention occurs. A hybrid deflection and retransmission-based routing scheme is proposed in [11] in which any contending bursts are initially deflected and if the resulting deflection routing fails in delivering all the bursts to the intended recipient, re-transmission of the affected bursts is re-attempted again on a different route. In terms of blocking and end-to-end latencies, the approach does perform quite modestly under low to moderate traffic loads. However, under heavy network traffic loads, an escalation of blocking probabilities dominates due to the repeated deflection and retransmissions increasing as well. This may lead to the overall network performance significantly degrading. To counter the rapid performance degradation under high traffic conditions, the number of deflections is limited by considering the residual hop count of all bursts encountering contention. A selective burst discarding scheme is proposed in [12], [13] in which if the contending bursts have already traversed more than the network radius, i.e. if the remaining number of hops that the contending burst has to traverse is less than the network radius, the bursts will be deflected.

A burst cloning-based scheme is presented in [14], in which a replica of the original burst is transmitted simultaneously to reduce the blocking probability. Should the original burst be blocked due to contention or wavelength congestion, its replica may still traverse through successfully to the destination node. Likewise, in [15], a Reflection Routing (RR) algorithm is introduced in which a contending burst is temporarily decoyed (deflected) to a neighboring node. The neighbor node in turn reflects it with the hope that wavelength reservation would be successful this time around. In a way, this scheme eradicates the need for fiber delay lines (FDLs). To reduce the reflection load from the neighboring node, a Load Balanced Reflection Routing (LBRR) algorithm is further incorporated so that only the adjacent neighboring node with the least levels of traffic loads will be designated as the reflection node.

In an attempt to address the load imbalances that may arise in the network as a result of deflection routing, a Gradient Projection-based RWA (GP-RWA) scheme is proposed in [16]. With this approach, if there exist multiples of linkdisjoint routes that can be computed using the Dijkstra algorithm between the sender and destination, the sender node dynamically selects a deflection route using a gradient projection approach to balance the load on the different sections as well as links in the network. Summarily, whereas lots of previous research work has addressed burst contention as well as deflection contention resolution approaches, however, all have the tendency to treat route selection and wavelength problems separately. It may be necessary to explore a cooperative approach in which both route selection and wavelength assignment are treated concurrently and in an integrated manner.

Hence in this paper, we propose a PIC-RWA scheme that couples with wavelength grooming to reduce blocking attributed to contention and wavelength congestions in the multiple domain network. The scheme attempts as much as possible to address both routing and wavelength jointly to reduce blocking probabilities in the core network and ultimately improving on effective throughput.

Summarily, the contributions of this paper are:

1) We propose and describe a PIC-RWA scheme that couples with wavelength grooming to improve the performance of a multiple domain network. In the process, the deflected traffic does not compromise the QoS of already existing connections in the network.
2). Of the chosen available candidate deflection routes, we elaborate on the general approach for selecting the wavelength to improve overall network performance and in particular the effective throughput as well as utilization.
3) The PIC-RWA scheme is further extended to a multi-domain backbone case in which each domain is managed independently. In this case, we focus on both border-to-border link traffic grooming as well as general resources dimensioning to ensure end-to-end QoS improvements in terms of probabilities for the lightpath connections as well as fairness.

The rest of the paper is outlined as follows: In the next section, we discuss deflection routing in general. This is followed by a detailed account of the proposed PIC-RWA scheme in section three. Section four examines traffic grooming as well as general resources dimensioning in a multiple domain backbone transport network. Section five presents and discusses both analytical as well as simulation results of the proposed scheme. Finally, we conclude the last section.

III. DEFLECTION ROUTING

The overall OBS network architecture comprises edge and intermediate (core) nodes interconnected via high-capacity DWDM optical links. Its generalized architecture is shown in Figure 2. The edge nodes directly interface the core network with the peripheral network sections. Peripheral network examples include Ethernet-based IP, wireless GSM access as well as enterprise cloud computing networks.

Each edge node is provisioned with adequate buffering from where data packets from various sources are aggregated and assembled into super-sized packets called data bursts. On the other hand, intermediate nodes provide limited or no buffering capabilities to ensure overall cost-effective rolling out of the OBS network. Consequently, the data bursts cannot be temporarily buffered before switching in them. Rather, an associated control packet (CP) is always dispatched before the release of the burst on the selected path. The information in the CP is used by the exit node to pre-configure the switch fabric ahead of the data burst arrival. In that way, data burst upon arrival will merely flyby through the switch to the desired output port without the necessity of pre-buffering it. It is necessary to set an offset time (t_{offset}) between the burst and its associated CP. As can be observed in Figure 2, burst arrivals from various input ports may be simultaneous, thus overlapping in time and wavelength (frequency). This might lead to one or more of them contending for the same output port, The contention occurrence may lead to the discarding of all but one contender. An alternative is to implement deflection routing contention resolution in which all but one contending burst are deflected to available least-cost paths. This necessitates selecting the paths in a such manner as not to compromise network performance in the affected section of the OBS network.

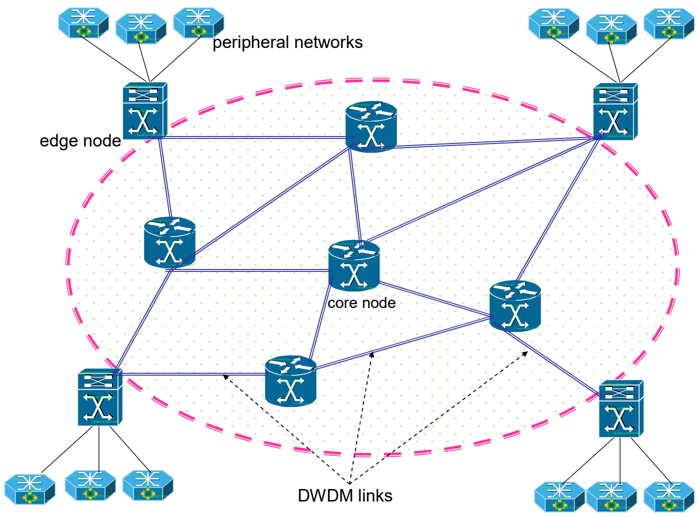


Fig. 2. OBS network with buffer-less interior nodes

The overall network can be represented as a graph $G(N,E)$, where N, $N=\overline{1,n}$ set of OBS nodes, and E $e=\overline{1,e}$, is the set of links. Each link $i \in E$ accommodates f_i fibers each with w_i active and usable wavelengths. If there is no free desired wavelength on the deflection link, wavelength conversion may be carried out, so accordingly the link $i = \in$ has a capacity $C_i = f_i w_i$ available wavelength channels. However, in this paper, we assume no wavelength conversion. Each end-to-end lightpath connection in the network must be assured of wavelength continuity. We define $\beta = \{1,2,\ldots,n(n-1)\}$ it to be the set of all source (x) and destination (y) pairs in the network. The corresponding traffic composed of bursts from the ingress node x to the egress node y is $m = \{x,y\} \in N$. The routing algorithm will always designate the least cost route (the route with minimum hops) as primary, and the rest regarded as the alternate. For a unidirectional S-D pair, $m = \beta$ and thus we can maintain the set:

$$\{\mathbf{U}_m(0), \mathbf{U}_{\mathrm{m,j_1}}(1), \mathbf{U}_{\mathrm{m,j_{11}}}(2),,..., \mathbf{U}_{\mathrm{m,j_2}}(T_m)\} \quad (1)$$

where $\mathbf{U}_{\mathrm{m}}(0)$ denotes the primary path, whereas $\mathbf{U}_{\mathrm{m},j}(d)$ represents the alternate deflection links with bursts deflected from j, and that the bursts have already been deflected d times. T_m is the maximum number of available deflection paths. Because a given burst cannot be deflected indefinitely, we thus impose a limit D of the allowable number of deflections on a given unidirectional source-destination pair m as being equal to:

$$T_m = \min\{T_m, D\} \quad (2)$$

As is known, an S-D path is often a concatenation of several links. We let ρ_m be the offered load on the source-destination pair m on a given link $j \in E$. On the same link, we distinguish two types of bursts; $k-$deflected burst is one that has already been deflected k times, $k \in \{1,2,...,T(m)\}$ and $0-$deflected burst being one that has not yet been deflected. Further, we define $a_j^k(m)$ it as the offered load by the $k-$deflection burst on the link j. The probability that a $k-$deflected burst will be blocked on this link is b_j^k. If we denote the first link on the source-destination pair m as j_1 and that it is the primary route, then the offered load to this link equals that offered to the source-destination pair, i.e. $a_{j_1}^0(m) = \rho_m$.
The offered load on the next (second) link j_2 is:

$$a_{j2}^0(m) = a_{j1}^0(m)\left(1 - b_{j_1}^0\right) = \rho_m\left(1 - b_{j_1}^0\right) \quad (3)$$

In the event of wavelength congestion on the next link j_3, the burst will be deflected onto the first alternate route j_4 and its offered load will be related to that offered to $j3$ as follows:

$$a_{j_4}^{k+1}(m) = a_{j_3}^k(m) b_{j_3}^k \quad (4)$$

Similarly, the load offered on the second-choice deflection route j_5 is;

$$a_{j_5}^{k+2}(m) = a_{j_4}^{k+1}(m) b_{j_4}^{k+1} = a_{j_3}^k(m) b_{j_3}^k b_{j_4}^{k+1} \quad (5)$$

In general, the total offered load of $k-$deflected bursts on a given link j for $k = 0,1,2,...,D$ is given by;

$$a_j^k = \sum_{m\in\beta} a_j^k(m) = \sum_{m\in\beta, j\in\mathbf{U}_{m,p}(k)} \rho_{m,p}^k \prod_{i\in E}\left(1 - I\left(i, j, \mathbf{U}_{m,p}(k)\right) b_i^k\right) \quad (6)$$

where, $\rho_{m,p}^k$, $k > 1$ is the offered load from link p to the $k-th$ deflection route and

$$\mathrm{I}(i, j, \mathbf{U}_{m,p}(k)) = \begin{cases} 1, & \text{If } i, j \in E \text{ along deflection route } \mathbf{U}_{m,p}(k) \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

The blocking probability for bursts with up to $k-$deflections is computed using the Erlang-B formula as follows:

$$\bar{b}_j^k = \mathbf{E}\left(\bar{a}_j^k, C_j\right) \quad (8)$$

Specifically, for OBS we assume that the load on the first link of source-destination pairs m is $a_{j_1}(m) = \rho_m$ and that offered to the next link is $a_{j_2}(m) = a_{j_1}(m)(1 - b_1)$, where b_j denotes the loss probability on the link j_i.
The load on any given link is:

$$a_j = \sum_{m\in\beta, j\in R(m)} \rho_m \prod_{j\in E}\left(1 - I_{OBS}(i, j, R(m) b_i\right) \quad (9)$$

where,

$$I_{OBS}(i, j, R(m)) = \begin{cases} 1, & \text{if } i, j \in E \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

Equation (10) is true provided link j is preceded by link i on along $R(m)$.
The blocking probability in an OBS network is expressed as:

$$B = \frac{\sum_{m\in\beta} \rho_m \prod_{i\in R(m)} (1 - I_{OBS})(i, R(m)) b_i)}{\sum_{m\in\beta} \rho_m} \quad (11)$$

The effective throughput of source-destination pairs m is therefore expressed as:

$$g(m) = a_{k(m)}(1 - b_{k(m)}) \quad (12)$$

The overall network's effective throughput is:

$$g(n) = \sum_{m\in\beta} g(m) \quad (13)$$

Similarly, if the utilization $U(j)$ of link j is:

$$U(j) = \frac{1}{C_j \sum_{i=0}^{C_j} i \times q_i(i)} \quad (14)$$

Where $q_j(i)$ denotes the steady-state probability of i busy wavelengths on the link j and C_j is the aggregate number of usable wavelengths on the link.

The effective utilization of the trunk is expressed as:

$$EU(j)\frac{1}{C_j}\sum_{m\in\beta} d(j,m)\times g(m) \tag{15}$$

In the preceding equation, the operator $d(j,m)$ is 0 if the link j is not part of the source-destination pairs m, and 0 otherwise.
Finally, the network's effective utilization is;

$$EI_n - \frac{1}{G}\sum_{j\in E} EU(j) \tag{16}$$

where G, is the aggregate number of unidirectional links in the network.

IV. NODE ARCHITECTURE AND PROPOSED PIC-RWA SCHEME

Figure 3 illustrates an architecture of an OBS node. The node is incorporated with both ingress and egress node functionalities. As an ingress node, it can generate, aggregate, and groom data bursts before transmitting them further into the interior. Overall, it performs operations such as data packets aggregating according to priorities in virtual queues (VQs) as well as priority and non-priority grooming of both local and transit burst traffic. It also carries out scheduling and BCP generation for each groomed burst. Its egress node functionalities include burst disassembly and further routing into the intended access networks.

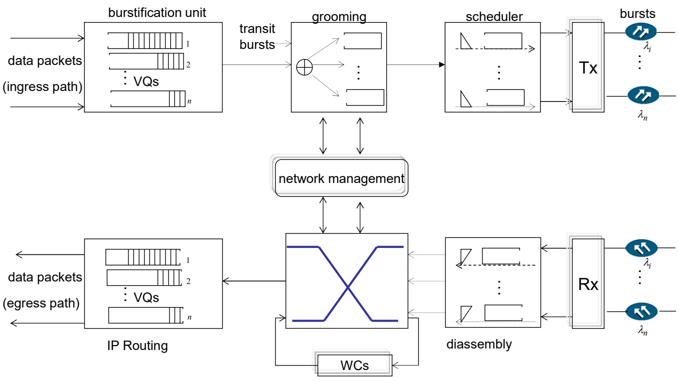


Fig. 3. Switch architecture with WCs

Its incorporated Network Management module enhances overall networking performance by assisting in making key decisions that help alleviate both contention and as well as wavelength congestion downstream. Notably, should contention occur, it is resolved by deflecting the contending data bursts to the least cost available alternate paths/links. The same module also keeps track of contention occurrences as well as wavelength congestion on all links emanating from it. This information is exchanged with other nodes and thus the selecting of candidate least cost deflection routes for contention resolution as well as wavelength congestion purposes will always be based on it.
In practice, in the event of the Network Management module collating an increase in the frequency of contention occurrences or wavelength congestion on a current active deflection path, it immediately invokes measures to remedy the situation. E.g. the node may temporarily suspend usage of that route or the congested wavelength. The latter may also be converted to any other available one, hence the presence of shared WCs.
The average processing power capabilities of the nodes will determine updating intervals to be adopted. This is to ensure that nodal computational congestion does not occur as this may further worsen general network performance. The architecture provided in Fig. 3 assumes that the switch fabric can only accommodate a limited number of wavelengths as well as links. Typically, all links have the same number of usable wavelengths. The route, as well as wavelength usage data acquired and maintained by the Network management module, will be relied upon to establish a wavelength usage index (UI), The UI is generally an indicator of variables such as least route length to the intended destination, wavelength availability, and suitability index (SI) [17],[18]. The SI ranks all usable available wavelengths from each node with regards to the history of associated burst contentions as well as wavelength congestion.

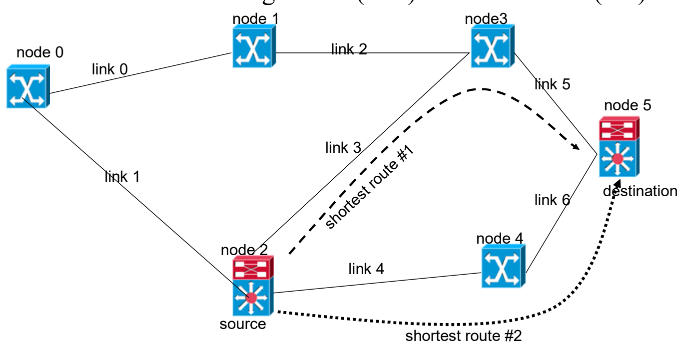
We further detail the proposal in terms of the following: route preprocessing, RWA at ingress nodes, RWA at intermediate nodes, and updating the SI.

A. Route Preprocessing

For each new assembled burst at an ingress node, all possible candidate shortest hop routes between the destination as well as adjacent nodes are computed. Each participating node's network management avails both the UI and SI values so that the most optimal route is ultimately chosen.

B. RWA at Ingress Node

For this scheme, we assume a one-way resource reservation protocol such as Just Enough Time (JET) or Just-In-Time (JIT).



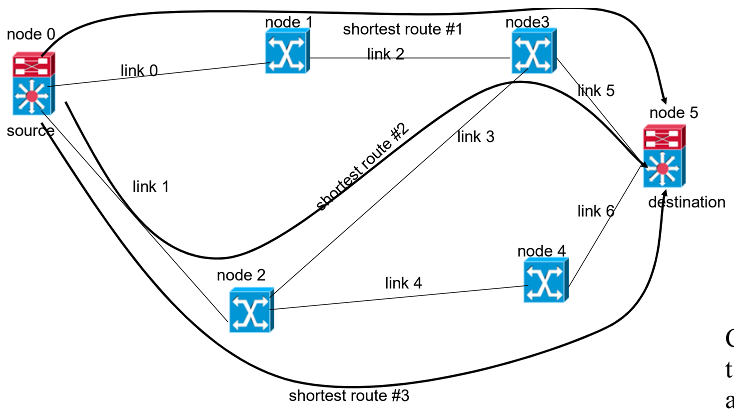
	λ_1	λ_2	λ_3	λ_4
link 1	0.3	0.2	0.5	0.7
link 2	0.4	0.2	0.3	0.6
link 3	**08 → 0.9**	0.7	0.5	0.1

Fig. 4. RWA at an ingress node

Since the ingress node maintains its output links directly, it simply refers to its current UI/SI values from which it will determine the least cost end-to-end route across the multi-domain network. At this stage, the availability of the wavelength at the output port (ingress node) is guaranteed since the source node manages and maintains its output links directly. Hence when scheduling and dispatching to all destinations except for adjacent nodes, the RWA is executed by referring to the available UI/SI tables. However, when sending bursts to an adjacent node, it opts for the least indexed UI/SI tabled values and in that way, rational usage of available resources is ensured. In other words, the ingress node will generally opt for highly indexed UI/SI values for non-adjacent nodes. This is illustrated in Figure 4. Note that in conjunction with the Network Management Module, should the reservation fail, the UI/SI values are immediately decremented accordingly.

C. RWA at Intermediates Node

Upon receipt of a wavelength reservation CP, the intermediate node assigns a link with a higher UI/SI value. This is exemplified in Figure 5. If the ingress node 0 selected output link 1 and is assigned λ_3 for scheduling the burst, the associated intermediate node 2 selects link 3 as the most suitable output link from the candidate shortest hop routes 2 and 3 by considering the SI values of link 3- λ_3 and link 4- λ_3 .



	λ_1	λ_2	λ_3	λ_4
link 1	0.3	0.2	0.5	0.7
link 2	0.4	0.2	03 → 0.2	0.6
link 3	08 → 0.9	0.7	0.5	0.1

Fig. 5. RWA at core (intermediate) node

If the resource reservation is successful at the intermediate node (node 2 in Figure 5), it is judged that its wavelength and output link is suitable not only for sending generated bursts but for relaying other bursts. Therefore, the intermediate node decreases the SI value of the wavelength on the link used for relaying bursts when the intermediate node receives the release message from the source node. However, if the reservation fails, it means that the pair of wavelength and output links will be unsuitable for relaying other bursts. Therefore, the intermediate node increases the SI value for the wavelength on the link used for relaying bursts when the intermediate node receives the NACK message returning to the source node.

D. Updating UI/SI Values

This is summarized in Figure 6. The normal operation of an OBS network requires that an ACK be sent back to the sending node as an indicator of end-to-end transmission success. However, should burst forwarding fail, a NACK will be sent back by the associated intermediate node where the contention or wavelength congestion occurred. Reception of either the ACK or NACK means the UI/SI values must be updated accordingly. E.g. the ingress node will increase both the UI and SI values upon receiving an ACK, whereas, otherwise a NACK will result in both values being decreased.

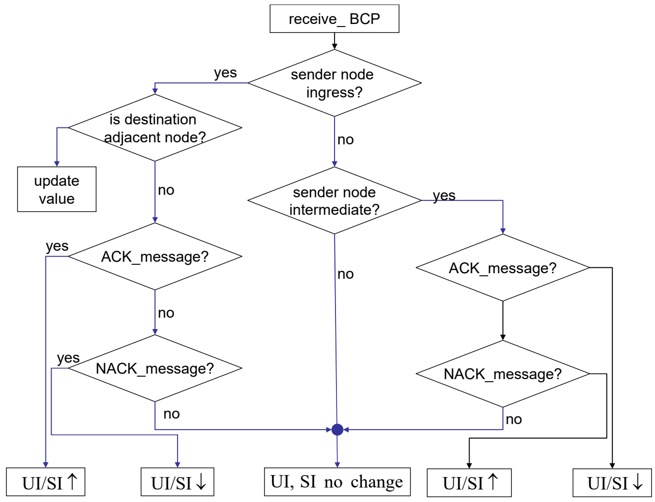


Figure 6. Updating of UI/SI values

Conversely, the UI/SI values are decremented when an intermediate node receives an ACK. If the destination node is adjacent, both values are not updated as the resources (wavelength and routes) were assigned without referring to the tables.

V. MULTIPLE DOMAIN RESOURCES DIMENSIONING

The last section assumed a single domain backbone transport network. In practice, such a network will span over a vast region or several counties hence likely to be in the form of interconnected multiple domain networks. Often, because of the diverse geographic locations of both network operators and end-users, many end-to-end lightpath connections will span across such multiple domains that are operated and managed independently.

In such a scenario, resource dimensioning must consider both intradomain as well as interdomain traffic. It would not be practical to implement the CDR scheme spanning multiple domains and as such information sharing with regards to resources management as well as contention control may be shared among the border nodes.

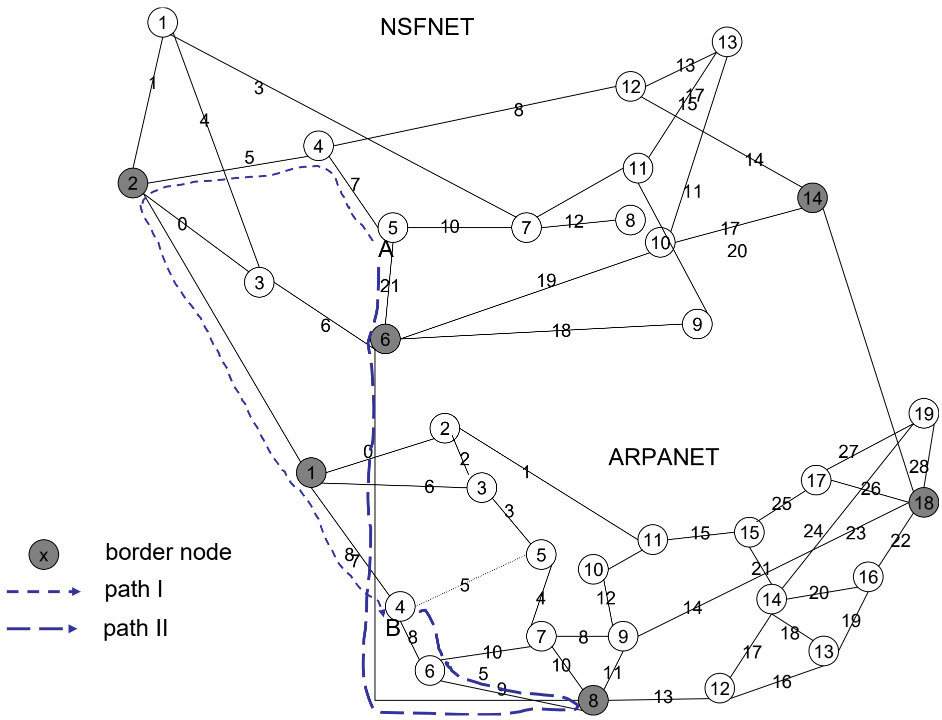


Fig. 7. Example multiple-domain network

An example of a joint domain network (ARPANET and NSFNET) is illustrated in Fig. 7 [19], [20]. To maintain high utilization of the border-to-border links, traffic grooming will be necessary. The grooming also improves contention performance.

A. Border to Border link Traffic Grooming

Primarily the purpose of grooming the connection request is to improve network utilization. We will assume that the connection requests are further prioritized so that grooming preference is given to higher priority class connection requests first [19]. The border-to-border node-link traffic grooming is essentially accomplished on a per-hop basis as the data bursts are destined for the same node hence several of them may be incorporated into a much larger single groomed data burst [20]. The entire grooming is summarized in Figure 8.

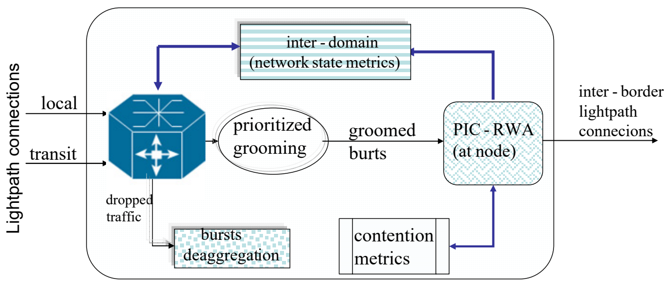


Fig. 8. Traffic Grooming. Adapted from [19]

Upon arrival at the other end of the hop, some fragments of the received groomed data burst are dropped (as local traffic) and further grooming can still be carried out with other bursts heading for the next hop. As soon as a data burst arrives at each grooming node, a timer based on the maximum further delay it can tolerate for the remaining hops in the network is set.

During the grooming, a grooming data burst will be released once it is timed out. The time-out value for data bursts in each VQ also considers the difference between the sum of remaining OBS source-destination propagation and node processing delays as well as disassembly time at the destination node.

We further redefine or add a few notations as follows:

F_N : number of available wavelengths on the link fiber.

B_N^i : number of groomed bursts on wavelength i .

b_n^i : data burst n utilizing wavelength λ_i .

B_n^i : groomed data burst n utilizing wavelength λ_i .

L_N^i : size of groomed data burst B_N^i .

a_i^n : arrival time of data burst n on wavelength i .

$\Delta_{i,j}^{p,q}$: intergap between groomed data bursts B_p^i and B_q^j .

e_i^n : terminating time of data burst n on wavelength i .

l_i^n : size (length) of data burst n on wavelength i .

T_s : processing time at each node.

$T_{\max}$: maximum size of groomed data bursts.

α : wavelength conversion cost.

With regards to the grooming on the border-to-border link, our objective would be to :

$$\text{maximise} \sum_{i=1}^{F_N} \sum_{n=1}^{B_N^i} x_i^n \tag{17}$$

where;

$$x_i^n = \begin{cases} 1 & \text{if data bursts } n, n-1 \text{ groomed on } \lambda_i \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

Note that the preceding equation $x_i^n \in \{0,1\}$ is an indicator of whether a data burst n and its predecessor $n-1$ are groomed together on the same wavelength λ_i or not.

Since the proportional delay slack distribution assumes that only WCs are available, equation (17) becomes:

$$\text{maximise} \sum_{i=1}^{F_N} \sum_{j=1}^{F_N} \sum_{k=1}^{F_N} \sum_{p=1}^{B_N^i} \sum_{q=1}^{B_N^i} \sum_{r=1}^{B_N^i} x_{i,j,k}^{p,q,r} - \alpha \sum_{i=1}^{F_N} \sum_{n=1}^{B_N^i} y_i^n \tag{19}$$

$$x_{i,j,k}^{p,q,r} = \begin{cases} 1 & \text{if data bursts } p, \text{and } q \text{ are groomed prior to r} \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

The previous equation $x_{i,j,k}^{p,q,r} \in \{0,1\}$ is an indicator that bursts p, q and r are scheduled on wavelengths i, j and k respectively. To indicate whether the burst's wavelength was converted or not, we have;

$$y_i^n = \begin{cases} 1 & \text{if wavelength converts when grooming data burst } n \\ 0 & \text{otherwise} \end{cases} \tag{21}$$

To ensure that a newly arrived data burst is wholly groomed to a single outgoing data burst and that the wavelength conversion can only be performed once, we have:

$$\sum_{j=1}^{F_N} \sum_{k=1}^{F_N} \sum_{q=1}^{B_N^j} \sum_{r=1}^{B_N^k} x_{i,j,k}^{p,q,r} \le 1, \tag{22}$$

$$\forall_i \in \{1,\ldots F_N\},\ \forall_{\mathrm{p}} \in \{1,\ldots B_N^i\}$$

$$\sum_{j=1}^{F_N} \sum_{k=1}^{F_N} \sum_{p=1}^{B_N^j} \sum_{r=1}^{B_N^k} x_{i,j,k}^{p,q,r} \le 1, \tag{23}$$

$$\forall_i \in \{1,\ldots F_N\},\ \forall_{\mathrm{q}} \in \{1,\ldots B_N^i\}$$

$$\sum_{k=1}^{F_N} \sum_{r=1}^{B_N^k} x_{i,j,k}^{p,q,r} \le 1, \tag{24}$$

$$\forall_i \in \{1,\ldots F_N\},\ \forall_j \in \{1,\ldots F_N\}, \forall_{\mathrm{p}} \in \{1,\ldots B_N^i\} \forall_{\mathrm{q}} \in \{1,\ldots B_N^j\}$$

To ensure that the wavelength conversion to another is as a result of grooming, the following condition will apply;

$$y_i^p = \sum_{j=1}^{F_N} \sum_{k \ne i} \sum_{q=1}^{B_N^j} \sum_{r=1}^{B_N^k} x_{i,j,k}^{p,q,r} + \sum_{j=1}^{F_N} \sum_{k \ne i} \sum_{q=1}^{B_N^j} \sum_{r=1}^{B_N^k} x_{j,i,k}^{p,q,r} \tag{25}$$

$$\forall_i \in \{1,\ldots F_N\},\ \forall_{\mathrm{p}} \in \{1,\ldots B_N^i\}$$

It is also necessary to limit the delay incurred by the data burst such that it does not exceed a preset maximum delay bound;

$$d_{i,j}^{p,q}.\delta \le \frac{d_s}{m},\ \forall_i, j \in \{1\ldots F_N\},\ \forall_p \in \{1\ldots B_N^i\}\ \forall_q \in \{1\ldots B_N^j\} \tag{26}$$

$$d_{i,j}^{p,q}.\delta \le D,\ \forall_i, j \in \{1\ldots F_N\},\ \forall_p \in \{1\ldots B_N^i\}\ \forall_q \in \{1\ldots B_N^j\} \tag{27}$$

To guarantee that a newly arriving data burst is accepted for grooming on a particular wavelength provided it may not trigger any potential conflicts such as contention or wavelength congestion upstream, we have the following set of conditions;

$$x_{i,j,k}^{p,q,r}.\left(g_k^r - \left(l_i^p + l_j^q + g_{i,j}^{p,q} - d_{i,j}^{p,q}\right)\right) \ge 0,\ \forall_q \in \{1\ldots B_N^j\} \tag{28}$$

$$\forall_p \in \{1\ldots B_N^i\} \forall_q \in \{1\ldots B_N^j\} \forall_r \in \{1\ldots B_N^k\}$$

$$g_k^r = a_k^r - e_k^{r-1},\ \forall_k \in \{1\ldots F_N\}, \forall_r \in \{1,\ldots B_N^k\} \tag{29}$$

$$g_{i,j}^{p,q} > 0,\ \forall_{\mathrm{i,j}} \in \{1\ldots F_N\}, \forall_{\mathrm{p}} \in \{1\ldots B_N^i\} \forall_{\mathrm{r}} \in \{1\ldots B_N^j\} \tag{30}$$

Finally, to regulate as well as impose a size limit of the groomed burst we have;

$$\sum_{p=1}^{B_N^i} \sum_{q=1}^{B_N^j} \sum_{r=1}^{B_N^k} x_{i,j,k}^{p,q,r} \left(l_j^q + g_{i,j}^{p,q} - d_{i,j}^{p,q}\right) \le T_{\max}, \forall_{i,j} \in \{1\ldots F_N\} \tag{31}$$

The burst grooming can be summarized by the following two algorithms.

Algorithm I : Link traffic grooming pseudocode

```
                    groo min g ( )
groom_same Wavelength ( );
if wavelength connection is available
  for λ = 1 to F_N do
    for each B^i_λ
    if |B^i_λ| = 1 // B^i_λ contains only one component burst
      Time_Limit = min(D, delay bound of b^i_λ);
        for λ' = 1 to F_N do
```

if $Groom\_WC\_(B^i_\lambda\_Time-Limit, \lambda')$
break ;
andif ;
andfor
if B^i_λ is not groomed
$Groom\_WC\_(B^i_\lambda\_Time-Limit, \lambda')$
endif
endif
endfor
endfor
$Groom\_Vidfilling(\ )$;
endif

Algorithm II : Link traffic grooming on a single wavelelength

for $\lambda = 1$ to F_N do
$i = B^i_\lambda$; // start grooming from the latest burst on wavelength λ
$j = 0$;
while $i > 1$ do
$j = j + 1$;
$B^j_\lambda = \phi + b^i_\lambda$; // initialize each burst
$L^j_\lambda = l^i_\lambda$
$k = d^i_\lambda$
$Time\_Limit = \min(D,$ delay bound of $b^i_\lambda)$;
$i' = i - 1$; // attempt togroomeach burst
if $k\delta < Time\_Limit$
while $i'' \geq 1$ do
//burst
// burst b^i_λ and b^i_λ cannot be groomed together
if (if $g^{i',i}_{\lambda',\lambda} > T_x$ *or*
$(l^i_\lambda + l^i_\lambda{}' + g^{i',i}_{\lambda,\lambda} - k\delta > T_{\max}$ break ;
else
$B^j_\lambda = B^j_\lambda + b^i_\lambda$; // add burst $'b^i_\lambda$ into the larger burst
$L^i_\lambda = l^i_\lambda + l^{i'}_\lambda + g^{i',i}_{\lambda,\lambda} - k\delta$;
$i' = i' - 1$; // continue to the next smaller burst
endif
endwhile
endif
$i = i'$;
endwhile
endfor

B. Resources Dimensioning

Resources dimensioning in a multi-domain backbone network must consider both internal as well as inter-domain traffic. This is because the individual domains are managed independently and hence a poorly resource provisioned domain may cause serious QoS degradation in other well-dimensioned domains. Routing of lightpath connections through independent multiple domains that are bound by contrasting policies may also raise fairness issues. An example is illustrated in Figure 7 in which a lightpath connection is established between nodes A and B of the joint NSFNET and ARPANET domain networks. Path #1 traverses nodes 4 and 2 on the NSFNET domain, node 1 (ARPANET) before reaching the destination B. Path #2 traverses node 6 (NSFNET) and then 8 and 6 on the ARPANET domain before reaching the destination B. Path #1 favors ARPANET as lesser nodes are involved in its domain, whereas on the other hand path #2 favors NSFNET. Provisioning extra resources for external traffic for each domain is the equivalent of dimensioning for additional traffic between an internal and border node. For simplicity's sake, we will assume a multiple domain network comprising two domains, with N and S set of nodes respectively The inter-domain links that connect the border to border node pairs have a capacity C^l_b. Given a set of R end-to-end lightpath requests, the internal and external traffic matrices are $T = \{(\lambda, \mu\}^R$ and $T' = \{(\lambda, \mu\}^{N+S}$ respectively.

For each domain, the aggregate external traffic originates from all designated border nodes set (N'). The equivalent external traffic on the local network includes arrivals and departures from all domain nodes $n \in N$ as well as border nodes $b \in N'$. The traffic load between a given external node s and the local node n may originate from any of the border nodes. We thus further can define a probability $p_{n,s,b}$ denoting the traffic between n and s originating from border node b, such that $\sum_{b \in N'} p_{n,s,b} = 1$. The total traffic matrix, in this case, is expressed by the following.

$$T'_L = \left\{ \left(\sum_{s \in S} \lambda p_{n,s,b} \sum_{s \in S} \mu p_{n,s,b} \right) \right\}^{N \times N'} \quad (32)$$

The projected internal and external traffic loads, i.e. the total traffic a given network can support without compromising QoS are;

$$\rho_{\text{int}} = \frac{\frac{\lambda}{\mu} \sum_{i \in R} TLS_i}{\sum_{e \in E} C_e} \quad (33)$$

$$\rho_{ext} = \frac{|N||S| \frac{\lambda}{\mu} \sum_{b \in N'} \frac{TSL(n,b)}{|N'|}}{\sum_{e \in E} C_e} \quad (34$$

where E is the set of links, as well as the topological shortest length (TSL). TSL is defined as the minimum number of hops for a lightpath connection in an unloaded (empty) network. The capacity from the set of inter-domain links is;

$$C_b^I = \left\lfloor \frac{\lambda}{\mu} \sum_{n\in N} \sum_{s\in S} p_{n,s,b} \right\rfloor \quad 35)$$

It is assumed that individual network domains are not obliged to furnish detailed routing and network status information to other domains. Concerning possible contention occurrences, they however may only broadcast the available shortest paths from source to each border for the source domain, from each border to all other borders for the intermediate domains, and from each border to the destination for the destination domain.

$$\Gamma = \frac{\lambda}{\mu} \sum_{n\in N\backslash N', n\in S, b\in N'} p_{n,s,b} \frac{TSL_{(n,b)} - \min_{n,k\in N'} TSL_{(n,k)}}{\min_{n,k\in N'} TSL_{(n,k)}} + \frac{\lambda}{\mu} \sum_{n\in N', s\in S, b\cup N'} p_{n,s,b} TSL_{(n,b)} \quad (36)$$

Note that in order to enhance QoS the broadcasted available shortest paths are chosen taking into account potential impairments levels such as dispersion.[21]

VI. ANALYSIS AND SIMULATION

In this section, we provide both numerical as well as simulation results for our proposed scheme. For numerical analysis, we assume a 14–node, OBS network that utilizes JET signaling. The network is shown in Figure 9. The nodes are numbered from 1 to 14 and are interconnected by a total of 33 links (also numbered from 1 to 33). We further assume burst arrivals at each ingress node to follow a Poisson distribution process. In all cases, the shortest path is also regarded as the least cost, and hence for all scenarios, it is designated as the primary route for each particular S-D pair.

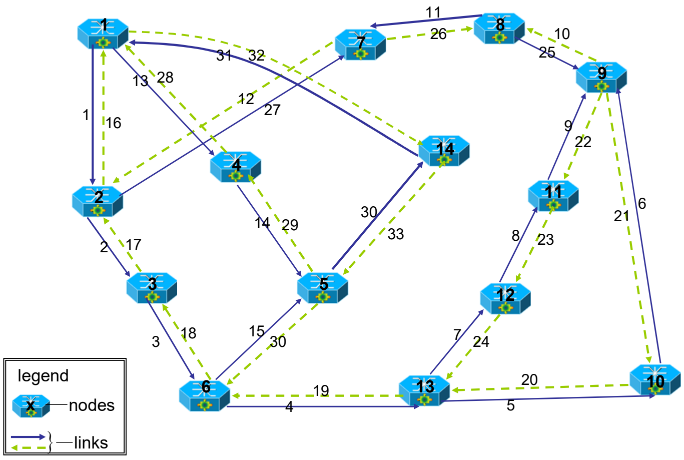


Fig. 9. A 14-Node Network

Table 1(a): S-D pairs in the forward direction(s)

No	#1	#2	#3	#4	#5	#6	#7
S	1	2	1	3	6	13	14
D	12	7	10	4	9	10	9
h	5	1	5	3	3	1	6

Table 2(b): S-D pairs in the reverse direction (s)

S	12	7	10	4	9	10	9
D	1	2	1	3	6	13	14
h	5	1	5	2	3	1	5

Table 3: S-D pair original (primary) defined route

S	D	$\#route$
1	12	$1\to2\to3\to4\to7$
12	1	$24\to19\to30\to29\to28$
2	7	27
7	2	12
2	10	$27\to26\to25\to21$
10	2	$6\to10\to11\to12$
3	4	$3\to30\to29$
4	3	$28\to1\to2$
6	9	$4\to5\to6$
9	6	$21\to20\to19$
13	10	5
10	13	20
14	9	$33\to30\to4\to7\to8\to9$
9	14	$21\to20\to19\to15\to30$

A. PIC-RWA Scheme's Performance

We commence this section by evaluating the proposed PIC-RWA scheme when confined to a single domain network. First of all, we carry out simple numerical evaluations as well as validation of the burst blocking probability as expressed by both equations (8) and (11). We take into cognizance that in cases where deflection routing contention resolution is implemented, the OBS network with capacity C tends to be unstable once the traffic load exceeds a certain threshold T . In this case, it is necessary to always reserve a capacity $C-T$ for primary traffic bursts to maintain stability in the network. The overall blocking probability can thus be also computed using the expression:

$$\bar{b}_k = \frac{\dfrac{\sum_{n=0}^{C-T-T} a_k a_o^n}{(T+n)!}}{\sum_{n=0}^{T} \dfrac{a_k^{-n}}{n!} + \sum_{n=0}^{C-T} \dfrac{a_k^{-T} a_o^n}{(T+n)!}} \quad (37)$$

For both numerical and simulation analyses, we assume the parameters in Table 3:

Table 4. Parameters for performance analysis

parameter	value
number of network links	**34**
wavelengths per fiber(link)	64
Each wavelength capacity	$10Gbps$
ave. burst length	1.5 MB
CP offset time (t_{offset})	0.35×10^{-3} sec$s$

Further, we assume that for each established S-D lightpath connection at each ingress node, the inter-arrival times of the generated bursts are exponentially distributed with parameter λ bursts per second. Likewise, the holding time at each node follows an exponential distribution with the parameter μ. We also assume that no FDLs or WCs are provisioned anywhere in the core network, hence only deflection contention resolution is implemented. Performance measures to be evaluated include burst blocking probability, effective throughput, as well as effective utilization. We carry out a performance comparison of the proposed PIC-RWA scheme versus other deflection routing contention resolution schemes such as:

- the traditional Shortest Path Deflection Routing (SPDR) which resolves contention by way of deflecting one of the contending data bursts to the first link on the second shortest path concerning the intended destination node. It is noted that this scheme has been used quite extensively as a reference when evaluating other schemes. It also appears in slightly varying versions in several literatures.

- A neural network (NN) based scheme is termed the adaptive reinforcement learning-based deflection routing scheme (RLDRS) [8]. With this scheme, should contention arise on the primary link, it chooses an optimal alternative route among the existing available ones based on both loss probability and delay when deflection is performed. It also imposes a limit on the number of authorized deflections of individual bursts to safeguard against surges in deflection routing traffic on the chosen alternate route.

- The predictive Q-learning deflection routing algorithm (PQDR) [24] primarily relies on predictive Q (PQ)-routing to generate optimal deflection routing contention resolution decisions. Note that PQ-learning maintains two separate Q-value estimates - the online estimate and target estimate. The online estimate follows the standard Q-learning update, while the target estimate is updated periodically.

- The contention-Based Limited Deflection Routing (CLDR) scheme, initially proposed in [25] makes limited deflection routing decisions based on some form of threshold-check function. Such decisions can be dynamically made at any intermediate node. Upon contention being experienced at a given node, the scheme dynamically determines if the burst should be deflected on a chosen deflection route or retransmitted from the source. Should the decision be to deflection route, then the same is done using a path that is based on minimization of a performance measure that combines distance and blocking due to contention.
- The Priority-based Wavelength Assignment (PWA) with shortest path routing to destination (PWA-link-dest) in which each network node selectively assigns wavelengths based on the wavelength priority information “learned” from its wavelength utilization history in a distributed manner.[12], [26].

By using equation (37) and the tabulated parameters in table 2, we establish several S-D pairs as in table 1. These are randomly selected. The shortest path is chosen by taking into account the updated SI and UI values. In all cases, the least cost (shortest path) is the designated primary route for each chosen S-D pair, and the candidate deflection routes are pre-assigned. We partly rely on the Waxman network topology generator in MATLAB for generating the various network topology scenarios. Note that in Waxman topology [27],[28].

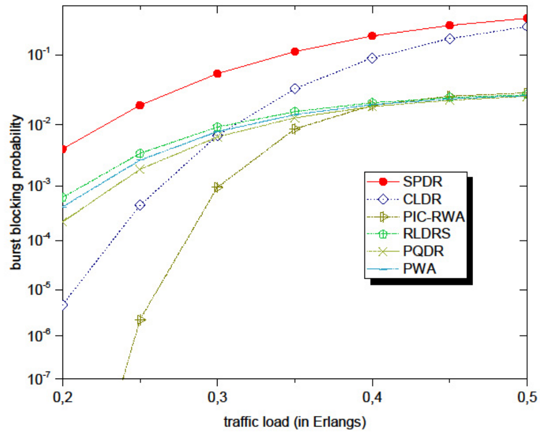


Fig. 10. Intra domain end-to end blocking comparison

Network nodes are distributed randomly. Each node is determined according to randomly generated coordinates, and a link is generated between two points with a certain probability. A time duration of about $\tau = 40ms$ is set as an allowance for the nodes to compute burst loss probability on each of their interfaces.

Plotted in Figure 10 are burst blocking comparisons for the various schemes as the network traffic is varied from light to moderate levels. Under low traffic conditions, both simulation and analytical results show that PQDR, RLDRS, PWA and the proposed scheme relatively outperform CLDR and SPDR. However, at moderate to high traffic loads, the proposed scheme slightly outperforms the rest. Its relatively good performance at moderate to high network traffic loads can be attributed to the fact that at low traffic loads, burst collisions (contention) as well as general wavelength congestion are non-existent or relatively less pronounced. However, as traffic increases, both burst contentions as well as wavelength congestions become more pronounced and thus because ingress nodes take into account both SI and UI values when determining primary routes, less of blocking is likely to be experienced with the proposed scheme.

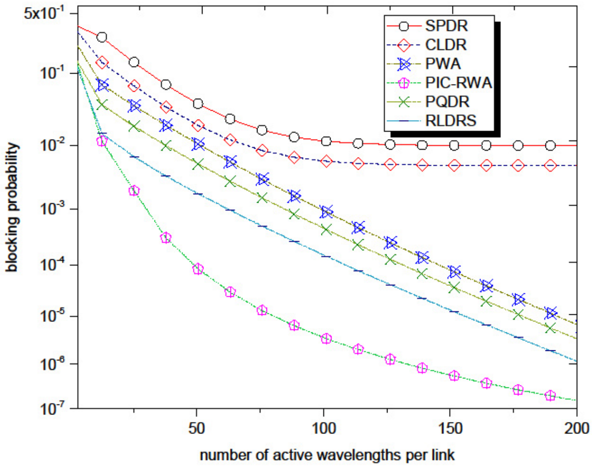


Fig.11. Loss probability as a function of the number of wavelengths per link/ fiber

For typical traffic loads up to about 0.65 Erlangs, the PIC-RWA reduces the blocking quite significantly, this being attributed to the enhanced deflection routing decision making that is distributed across all the nodes, in the network domain. Likewise, the CLDR initially outperforms the SPDR, partly because of the threshold check function, which is performed at the node experiencing burst contention.
Comparisons on the effect of regulating the number of usable wavelengths per fiber or link are also carried out by varying the number of available wavelengths with traffic load. By comparison, it is observed from Figure 11 that the proposed scheme will require a much lesser number of wavelengths to maintain a certain QoS in terms of blocking. E.g. by fixing the traffic load to 0.6, the proposed scheme will require about 30 wavelengths per fiber (link) to maintain a burst blocking probability of 10^{-3}, whereas for the same traffic load PQDR will require about 62 wavelengths.

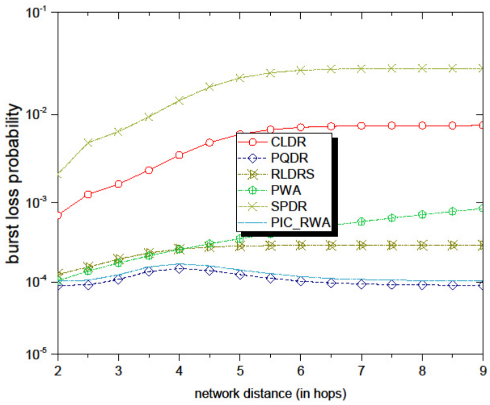


Fig.12. Blocking probability versus S-D distance (in hops)

Figure 12 plots the burst loss probability as a function of network distance measured in hops. The traffic load is fixed at 0.07. The number of hops commences from two to nine. As can be observed from the same figure the performance of SPDR, and CLDR significantly worsen as the number of hops increases.

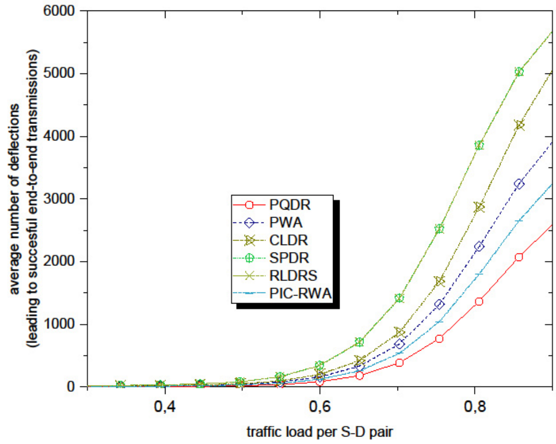


Fig. 11 Average number of deflected bursts versus network traffic load.

SPDR deflects one of the contending bursts to the next least-cost route (based on hop count) and hence blocking can still be encountered. Similarly, CLDR on the other hand considers both hop count together with expected burst loss
probability along the chosen alternate route, hence its performance betters.
RLDRS considers residual hop count to intended destination into consideration when generating the reward signals that are used to update Q-values, this resulting in lower burst blocking probabilities. PQDR on the other hand will not always rely as well as utilize Q-values in making deflection decisions, as this would result in the selection of longer paths and higher burst loss probabilities. Note that bursts are likely to encounter contention when the lightpath connection spans over several hops. The grooming approach in PIC-RWA ensures that different lightpaths can be merged as when necessary and consequently reducing contention. Thus, its performance in terms of burst loss probabilities is relatively better.

By default, when a burst encounters contention at any intermediate node, the contention is resolved by way of deflection routing as we assumed no provisioning of FDLs and WCs in the network. The same applies when wavelength congestion is experienced on the intended primary shortest path route, A plot of the number of deflections as a function of traffic load is provided in Figure 13. At low traffic loads, all schemes minimize the number of deflections as there are lesser cases of burst contention as well as wavelength congestion. However, as the traffic increases beyond 0.6, the number of deflections rapidly increases exponentially across all the schemes. The PQDR generally outperforms the rest.

This is because the scheme thrives on compelling each network node selectively assigning wavelengths based on the wavelength priority information "learned" from its wavelength utilization history in a distributed manner.

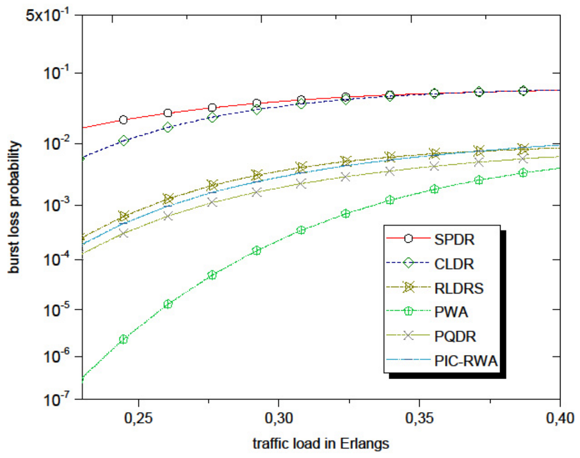


Figure 14. Burst loss probabilities for 6-hop S-D pairs

Neighboring nodes in a particular section of the network tend to assign different wavelengths to avoid contention. Although the proposed scheme performs well, it is however outperformed by the PWA because the updating of SI and UI values often cannot keep pace with the frequency of contentions and wavelength congestion at high traffic loads.

We further explore the performance of individual end-to-end lightpath connections. As such, we compare the burst blocking probabilities of individual S-D pairs depending on the network distance (number of hops) between them. As can be seen in Figure 14, the proposed scheme experiences relatively lower burst blocking probabilities. However, this is at the expense of utilizing more network resources.

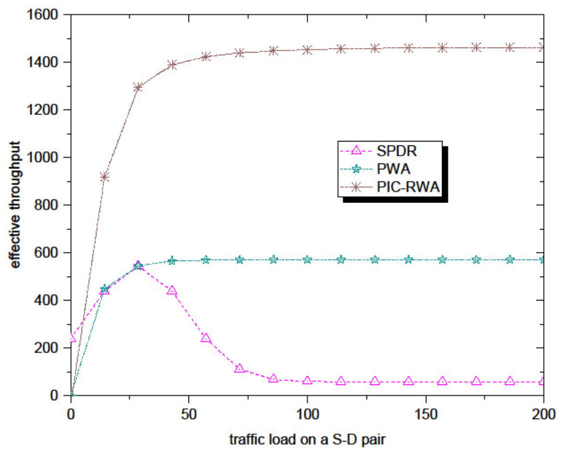


Fig. 15. Effective throughput per S-D pair as a function of offered load

Performance comparisons of the proposed scheme with regards to both the effective throughput and utilization are shown in Figures 15 and 16 respectively. As emphasized in earlier sections, all lightpath connections are set up on the shortest paths, and as such bursts that require a relatively fewer number of hops are prioritized and they utilize relatively fewer network resources. Hence in each case for each S-D pair, the path with the least number of hops is selected. Each link fiber has a fixed number of wavelengths and the burst arrival rate to each S-D pair is the same. In Figure 15, the proposed scheme's goodput quickly increases to a high level in comparison to the other schemes. As expected, the goodput of the RR-SP initially increases in proportion to the offered traffic load, but quickly saturates and then starts declining. The declination is attributed to the high levels of both contentions as well as wavelength congestions being experienced throughout the network as the traffic increases. The combined PWA schemes will saturate at a slightly higher level.

With regards to the utilization, we observe from Figure 16 that for light to moderate traffic loads, the network is generally underutilized. Since the proposed scheme relies on the current SI and UI values, its overall utilization is initially quite low, but steadily peaks up since the scheme allows the deflection of contending bursts thus more bursts can reach their destination.

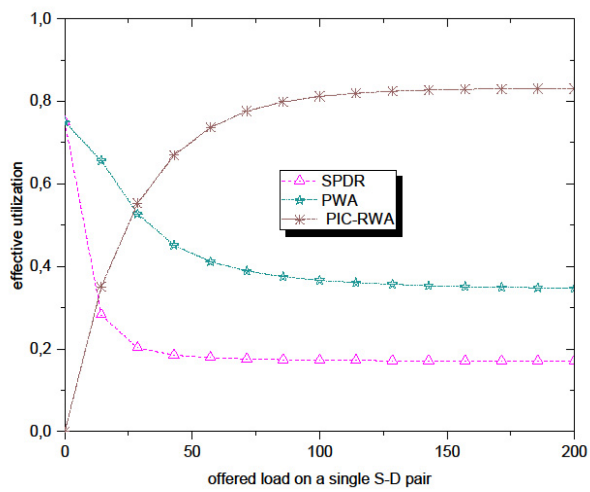


Fig. 126. Effective utilization per S-D pair as a function of offered load

This effectively improves the goodput as well as lowering the blocking performance.

B. *Border-to-Border Link Traffic Grooming*

Despite the few challenges stated in the preceding sections, the proposed scheme does significantly contribute to effective control and signaling information processing at each node. One way of further improving the overall network's performance is to significantly reduce BCP processing by way of grooming smaller bursts. Grooming further aids in enhancing network performance as follows:

- In terms of contention control, smaller data bursts intended for a common destination will be streamlined onto one single groomed data burst.
- Fewer bursts in the network imply better wavelength utilization and a reduction in wavelength congestion.

- The grooming also significantly reduces blocking as a result of the contention control and reduced wavelength congestions.

As outline earlier, because practical optical backbone transport networks are multi-domain in nature, the grooming will only be carried out at border nodes. The overall objective is to minimize the number of data bursts in the core network and at the same time promoting wavelength efficiency. In that way, the number of WCs in the network is reduced, hence striking a balance between grooming and associated costs.

In the simulation, the grooming algorithms process the BCPs at fixed time intervals. Full wavelength conversion can be implemented when necessary, with the aid of WCs available.

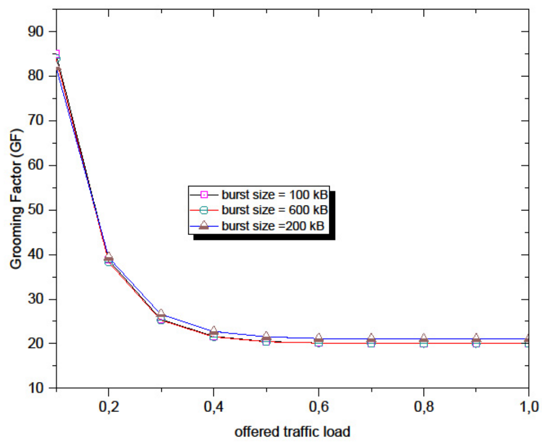


Fig. 13. Grooming performance as a function of burst sizes

The grooming performance is defined by a grooming factor (GF) being a measure of the ratio of groomed bursts post grooming to the aggregate number of original smaller bursts in the grooming queues (*VQs*).

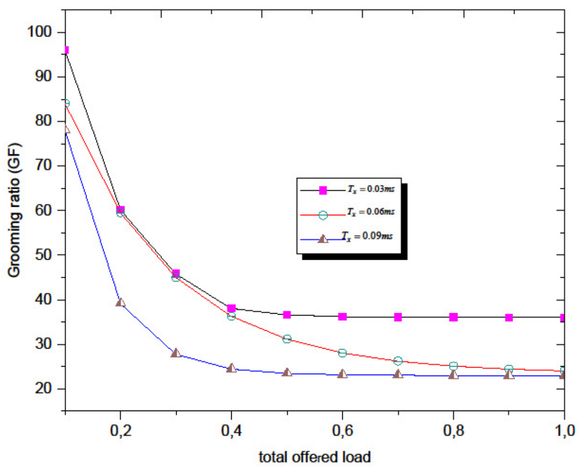


Fig. 14. Grooming performance as a function of switching time

As can be observed from Figure 17, at low traffic loads, fewer bursts are available for the grooming process and hence the *GF* is quite poor. As the traffic builds up, the dropping of small-sized bursts by the OBS scheduler is higher because of the relatively smaller inter-burst gap. However, as the traffic load increases above 0.6 . the grooming performance improves, and all burst sizes tend to have the same grooming performance.

The set switching time can also affect the grooming performance. In Figure 18, various switching times were utilized and overall, it is observed that the grooming performance improves with increases in the switching time.

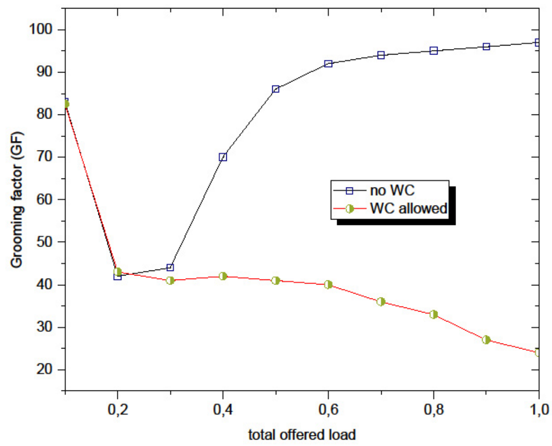


Fig. 15. Grooming performance and WCs

At this point, we assume that our model border node architecture incorporates a limited number of WCs are available on a common sharing basis and thus wavelength conversion is available. We observe from Figure 19 that grooming performance is more enhanced when wavelength conversion is available since data is not available because bursts utilizing different wavelengths can still be groomed together.

VII. CONCLUSION

In this paper, we proposed a prioritized (indexed) cooperative-based routing and wavelength assignment (PIC-RWA) scheme that couples with wavelength grooming for inter-border traffic to reduce both contention and wavelength congestions. The individual domains are assumed to interconnect via designated border nodes and as such grooming traffic on border-to-border links is seen to significantly enhance the overall network's performance in that it will result in the reductions of the number of BCPs to be processed at nodes. Grooming further aids in enhancing network performance in terms of contention control as smaller data bursts intended for a common destination will be streamlined onto a single groomed data burst. Fewer bursts in the network imply better wavelength utilization and a reduction in wavelength congestion. The grooming also significantly reduces blocking as a result of the contention control and reduced wavelength congestions. By also cooperatively dimensioning resources in individual domains network performance in terms of blocking probabilities can be improved.

In this respect, it is generally noted that the performance, as well as fairness of various resources dimensioning approaches in a multi-domain backbone transport network, can be best achieved by the individual domains collectively sharing key information. Metrics to measure the traffic loads, as well as the degree of fairness in resources, is also necessary to enhance overall network performance. In future we are looking at further enhancing the performance of the PIC_RWA scheme by incorporating a priority based routing and wavelength assignment scheme with incorporation of a traffic grooming mechanism (PRWATG) [19]. In so doing, both the chosen routes as well as wavelengths will be prioritized taking physical layer impairments (notably dispersion) [21] into account. The ultimate aim would be to further reduce both intra and inter domain connection blockings (as well as congestion), whilst at the same time, maintaining high utilization of the selected links.

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