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Research Article

# A RWA Scheme For Deflected Bursts in Optical Burst Switched Networks

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## Abstract

All Optical Burst Switched (OBS transport networks are often characterized by frequent occurrences of both contention and wavelength congestion. Their occurring often leads to degradations in overall network performance in handling moderate to high traffic levels, and all this leading to increases in data burst losses. Deflection routing contention resolution is quite popular in combating both types of congestions and ultimately leading to improvements in overall network throughput. However, it is necessary that network throughput always balance with effective utilization. In this paper, we propose a prioritized (indexed) cooperative based routing and wavelength assignment (PIC-RWA) scheme that reduce both contention and wavelength congestions. Performance results indicate that it significantly improves overall network performance in terms of improved effective resources utilization.

***Keywords:*** *deflection routing, contention, wavelength congestion, wavelength index*

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## 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 end 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). 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 as this would also lead to an increase in 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]. This is because some of the lightpath connections are likely to be discarded at intermediate nodes as a result of either contention or general wavelength congestion occurrences [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. Besides, it can also contribute to differential delays or jitter for successive bursts which belong to the same application or service and thus are 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 implemented in a controlled manner.

## Related Work

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). Their aim is 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 algorithm on choosing deflection paths (routes) is further 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 algorithm's complexity however lies in the involvement of multitudes of parameters for determining and defining pre-emption probabilities and policies.

A Deflection Routing algorithm for implementation in an anycast-based OBS grid is proposed by the authors in [9]. However, the algorithm does not appear to address or alleviate the contention problem satisfactorily. Fairness and data burst loss owing to cascading constraints when bursts have traversed long hop counts in the OBS network is explored in [10]. The authors herein propose a preemptive scheduling technique in which newly arriving bursts with higher priority (based on the number of hops already traversed) may pre-empt 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 arbitrarily deflected and if the resulting deflection routing does not succeed 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, the blocking probabilities will also increase. This is owing to the deflection and re-transmissions traffic increasing as well. This may lead to significant degradation of overall network performance. To counter the rapid performance degradation under high traffic conditions, the number of deflections is limited by taking into account 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]. With this scheme, 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 successfully to the intended destination node. In [15], a Reflection Routing (RR) contention control scheme is presented in which one of the contending bursts is temporarily decoyed (deflected) to a neighboring node. The neighbor node will in turn shortly afterward reflect it back 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). In order to reduce the reflection loads on the reflection link(s), the scheme further incorporates a Load Balanced Reflection Routing (LBRR) algorithm. The algorithm's main role is to ensure that each time contention occurs, only an adjacent neighboring node with the least levels of traffic loads will be chosen as the candidate reflection node. The work in [16] proposes a Contending Burst Copying-based Reflection Routing (CBCRR) contention resolving scheme that resolves burst contention by way of a given node replicating one of the contending bursts before sharing it with an adjacent node. It is more or less similar to the RR proposed in [15]. Upon receiving the replicated burst, the adjacent node reflects it back to the sender node for pre-reserving the same wavelength again. The scheme's performance, though comparably good, it, however, may lead to unnecessary surges of traffic between the core and its adjacent nodes. A controlled retransmission-based contention resolution scheme that takes into account the effect of the relevance of both fresh and retransmitted incidence traffic from the various links when computing both link blocking as well as byte loss probabilities are discussed in [17], [18]. The effects of introducing wavelength converters (WCs) on the overall performance of the scheme is also investigated. Further, a comparison between controlled and uncontrolled retransmission-based versions of the same scheme is carried out in which the earlier appears to outperform. However, the authors concede that overall retransmission-based schemes may not always provide a consistent QoS for real-time loss intolerant traffic. Delay bounds for segmented bursts-based approaches have been discussed in various studies e.g. [19], [20], [21], [22]. ON the basis that the various contention resolution strategies, including burst segmentation, will render varying levels of quality of transmission (QoT), the authors in [22] thus suggesting that burst segmentation should be applied only to lower priority bursts. As a consequence, relatively fewer buffering resources such as FDLs will be required, and also a reduction in lower priority burst loss probabilities. This is on the assumption that each composite segmented burst comprises both lower (tail end) and higher (head-end) priority sections, in which by default the tail end will be otherwise discarded in the event of contention occurring. According to [22], when contention occurs, the lower priority segments are diverted to an FDL. Deflection routing and retransmission-based contention resolving schemes are reviewed extensively in [23]. In the same work, the authors introduce a dynamic hybrid retransmission deflection routing (DHRD) scheme which blends both deflection routing and retransmission in a bid to improve overall burst loss probabilities. In analyzing the DHRD scheme the focus is on the overall impact of resulting retransmission and deflection traffic on overall network throughput. The retransmission traffic is regulated by way of utilizing two retransmission parameters; retransmission probability (D1) and persistent probability (D2) to control the rates of data transmission with the help of updated values of the prevailing burst loss rates. Overall, the retransmissions will still compromise the QoS of real-time loss-sensitive applications. The deflection routing contention mechanisms ultimately trigger traffic load imbalances in the network. The Gradient Projection-based RWA (GP-RWA) scheme proposed in [24] seeks to avoid any traffic load imbalances that may arise in the core network. With this approach, if there exist multiples of link-disjoint routes that can be computed using the Dijkstra algorithm between the sender and destination nodes, the earlier dynamically selects a deflection route using a gradient projection approach so as 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 congestion 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.

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 presents and discusses both analytical as well as simulation results pertaining to the proposed scheme. Finally, we draw conclusions.

## deflection routing contention resolution

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 1. 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 prior to switching 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 1, 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 bursts are deflected to the available least cost paths. This necessitates selecting the paths in such a manner as not to compromise network performance in the affected section of the OBS network.

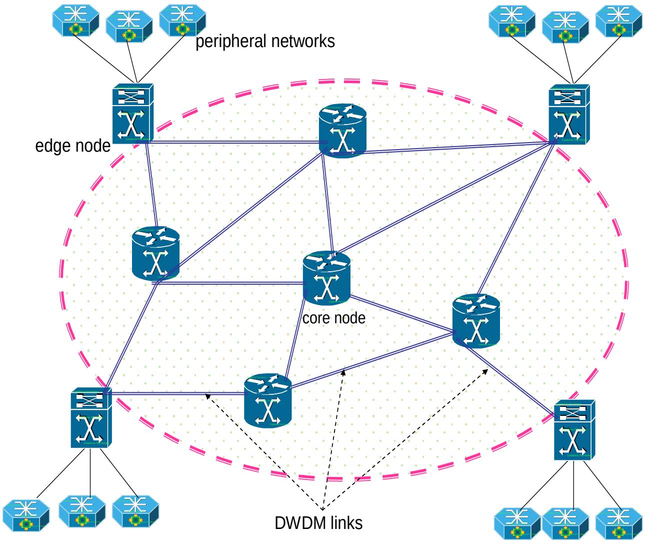


**Figure 1: OBS network with buffer-less interior nodes**

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. In the event that 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 $C_i=f_iw_i$ for 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 $\beta=\{1,2,...,n(n-1)\}$ 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 an alternate. For a unidirectional S-D pair, $m=\beta$ and thus we can maintain the set:

$$\{\mathbf{U}_m(0),\mathbf{U}_{\mathrm{m},\mathrm{j}_1}(1),\mathbf{U}_{\mathrm{m},\mathrm{j}_{11}}(2),,...,\mathbf{U}_{\mathrm{m},\mathrm{j}_2}(T_m)\} \qquad (1)$$

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 $D$ on the allowable number of deflections  on a given unidirectional source-destination pair $m$ as being equal to:

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

As is known, an S-D path is often a concatenation of several links.  We let $\rho_m$ be the offered load on the source-destination pair $m$ of a given link $j\in E$. On the same link, we distinguish two types of bursts; a $k-$type deflected burst is one that has already been deflected $k$ times, $k\in\{1,2,...,T(m)\}$ and a $0-$type deflected burst being one that has not yet been deflected. Furthermore, we define $a_j^k(m)$ 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. $a_{j1}^0(m)=\rho_m$.

The offered load on the next (second) link $j_2$ is:

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

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

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

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

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

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

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

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

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

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

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

Specifically, for OBS we assume that the load on the first link of the source –destination pairs $m$ is $a_{j1}(m) = \rho_m$ and that offered to the next link is $a_{j2}(m) = a_{j1}(m)(1 - b_1)$, where $b_j$ denotes the loss probability on link $j_i$.

The load on any given link is:

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

where,

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

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:

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

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

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

The overall network’s effective throughput is:

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

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

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

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.

## Proposed Scheme

Figure 2 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 network(s).

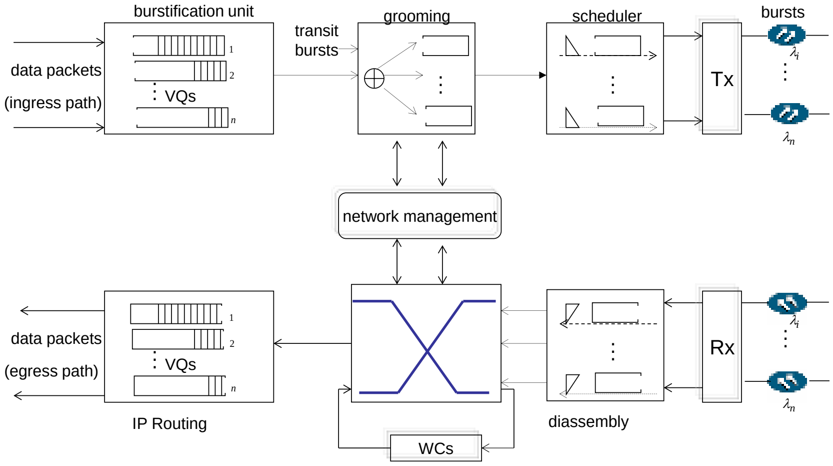


Figure 2: Switch architecture

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. or 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 occurrence or wavelength congestion on a current active deflection path, it immediately invokes measures to remedy the situation. E.g., the node may temporarily suspend the 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.

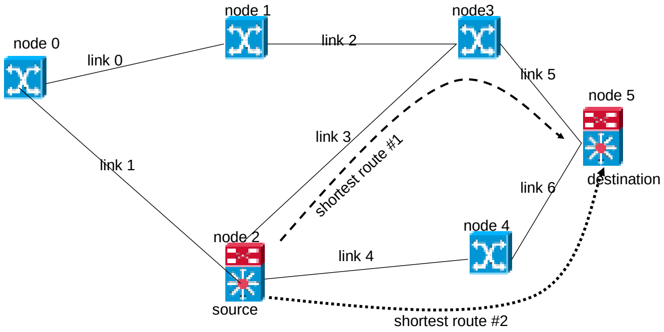
The average processing power capabilities of the nodes will determine the updating intervals to be adopted. This is to ensure that nodal computational congestion does not occur as this may further worsen the general network performance. The architecture provided in Fig. 3 assumes that the switch fabric 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). The SI ranks all usable available wavelengths from each node with regard 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 Processing*

For each new assembled burst at an ingress node, all possible candidate shortest hop routes between the source and 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).



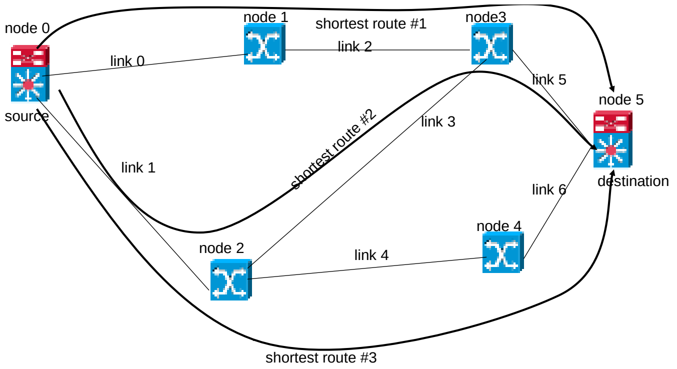
| | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ |
|---|---|---|---|---|
| link 1 | 0.3 | 0.2 | 0.5 | 0.7 |
| link 2 | 0.4 | 0.2 | 0.3 | 0.6 |
| link 3 | **08→0.9** | 0.7 | 0.5 | 0.1 |

**Figure 3: 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 3. Note that in conjunction with the Network Management Module, should the reservation fail, the UI/SI values are immediately decremented accordingly [25].

### C. *RWA at Intermediate 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 4. If the ingress node #0 chose an outgoing link 1 and wavelength $\lambda_3$ for scheduling the data burst, the associated core node #2 will opt for link 3 as the desired outgoing link after taking into consideration the SI values of candidate link 3-$\lambda_3$ and 4-$\lambda_3$.



| | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ |
|---|---|---|---|---|
| link 1 | 0.3 | 0.2 | 0.5 | 0.7 |
| link 2 | 0.4 | 0.2 | $03 \rightarrow 0.2$ | 0.6 |
| link 3 | $08 \rightarrow 0.9$ | 0.7 | 0.5 | 0.1 |

**Figure 4: RWA at a core (intermediate) node**

Should the wavelength reservation succeed at the core node #2 (Figure 4), it thus can be used for both fresh bursts as well as those that require deflection. However, if the reservation fails, it means that the pair of wavelength and output links will be unsuitable for relaying other bursts. The intermediate node will increment the SI value accordingly upon the reception of a NACK message returning to the source node.

### 4.4 Updating UISI Values

This is summarized in Figure 5. 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. The reception of either an 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. Conversely, the UI/SI values are decremented when an intermediate node receives an ACK.

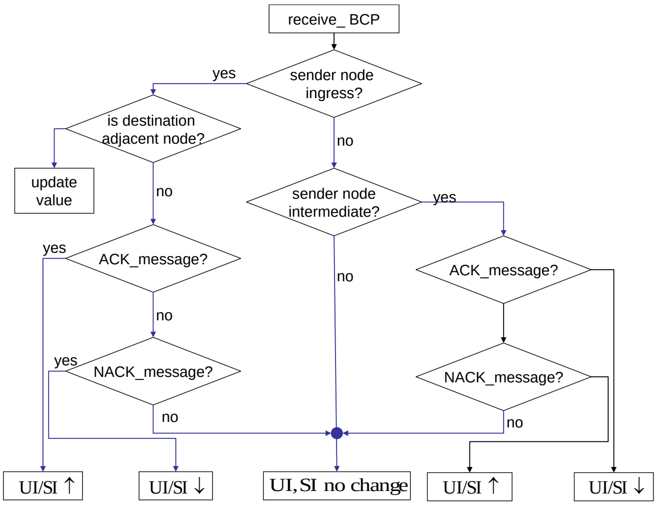


Figure 5: Updating of UI/SI values

If the destination node is adjacent, both values are not updated as the resources (wavelength and routes) were assigned without referring to the tables.

## Analysis

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 7. 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 S-D pair.

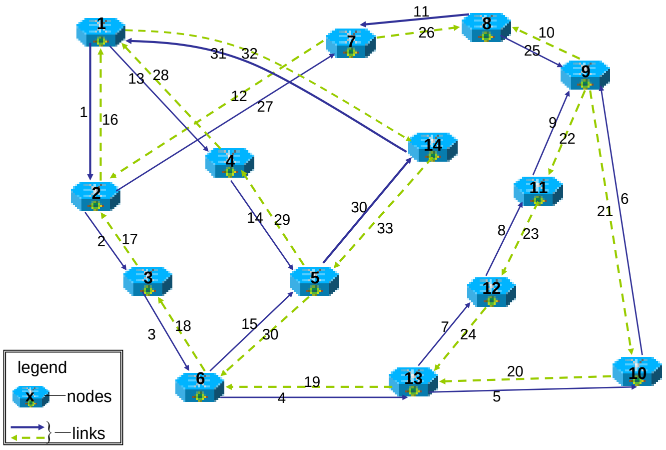


Figure 7: A 14-Node Network

**TABLE 1: 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: 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 | $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 7$ |
| 12 | 1 | $24 \rightarrow 19 \rightarrow 30 \rightarrow 29 \rightarrow 28$ |
| 2 | 7 | 27 |
| 7 | 2 | 12 |
| 2 | 10 | $27 \rightarrow 26 \rightarrow 25 \rightarrow 21$ |
| 10 | 2 | $6 \rightarrow 10 \rightarrow 11 \rightarrow 12$ |
| 3 | 4 | $3 \rightarrow 30 \rightarrow 29$ |
| 4 | 3 | $28 \rightarrow 1 \rightarrow 2$ |
| 6 | 9 | $4 \rightarrow 5 \rightarrow 6$ |
| 9 | 6 | $21 \rightarrow 20 \rightarrow 19$ |
| 13 | 10 | 5 |
| 10 | 13 | 20 |
| 14 | 9 | $33 \rightarrow 30 \rightarrow 4 \rightarrow 7 \rightarrow 8 \rightarrow 9$ |
| 9 | 14 | $21 \rightarrow 20 \rightarrow 19 \rightarrow 15 \rightarrow 30$ |

### *A. PIC-RWA 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:

$$\bar{b}_k = \frac{\dfrac{\sum_{n=0}^{C-T} \bar{a}_k^{T} a_o^n}{(T+n)!}}{\sum_{n=0}^{T} \dfrac{\bar{a}_k^{n}}{n!} + \sum_{n=0}^{C-T} \dfrac{\bar{a}_k^{T} a_o^n}{(T+n)!}} \qquad (17)$$

For both numerical and simulation analyses, we assume the parameters in Table 4:

**TABLE 4. Parameters for performance analysis**

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

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 $\lambda$ bursts per second. Likewise, the holding time at each node follows an exponential distribution with the parameter $\mu$. 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 with respect to 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 works.
- A neural network (NN) based scheme referred to as the adaptive reinforcement learning-based deflection routing scheme (RLDRS) introduced in [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.

- A predictive Q-learning deflection routing algorithm (PQDR) [28] that 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 the 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 [29] 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, routed, 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], [27].

By using equation (17) 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 considering 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 [30],[31]. 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.

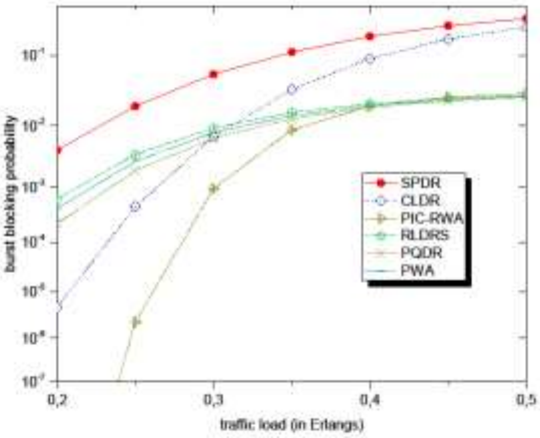


**Figure 8: End-to-end blocking comparisons.**

Plotted in Figure 8 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 blocking is likely to be experienced with the proposed scheme. 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.

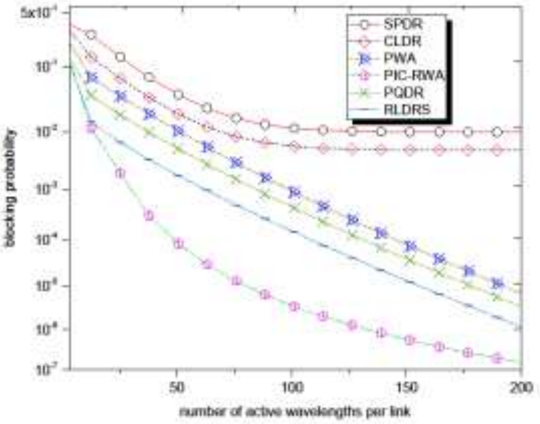


**Figure 9: Loss probability as a function of the number of wavelengths per link/ fiber**

Comparisons on the effect of regulating the number of usable wavelengths per fiber or link is also carried out by varying the number of available wavelengths with traffic load. By comparison, it is observed from Figure 9 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.

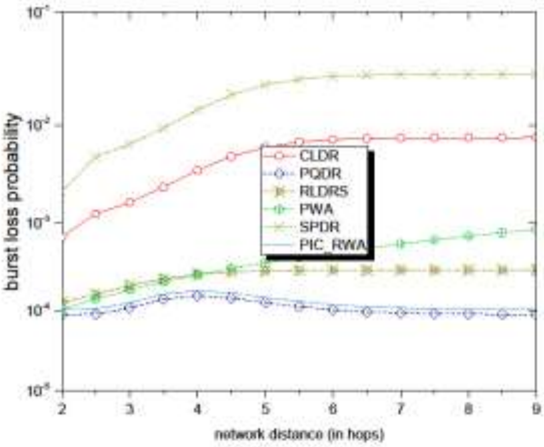


**Figure 10: Blocking probability versus S-D distance (in hops)**

Figure 10 plots the burst loss probability as a function of network distance measured in hops. The traffic load is fixed (e.g 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. 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.

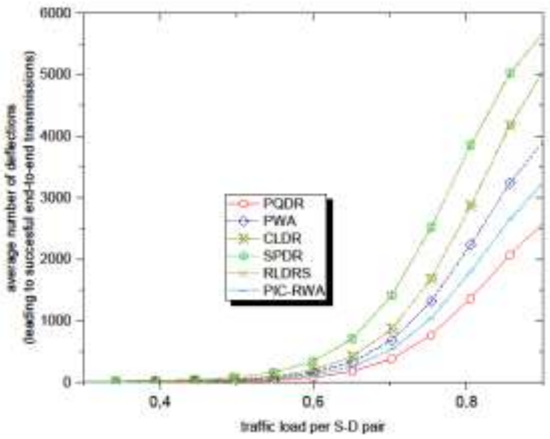


**Figure 11: Average number of deflected bursts versus network traffic load.**

RLDRS takes into account 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 upon utilizing 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 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.

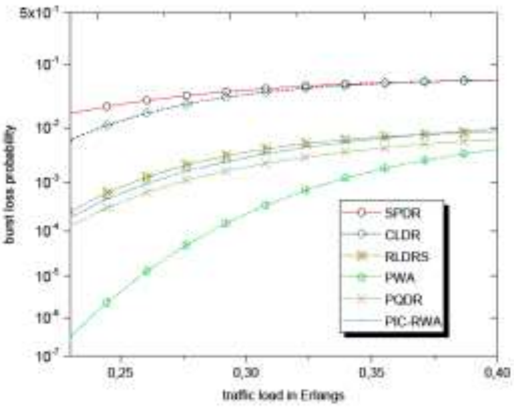


Figure 12: Burst loss probabilities for 6-hop S-D pairs

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 11. 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 to selectively assigning wavelengths based on the wavelength priority information "learned" from its wavelength utilization history in a distributed manner. Neighboring nodes in a particular section of the network have the tendency 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 12, the proposed scheme experiences relatively lower burst blocking probabilities. However, this is at the expense of utilizing more network resources.

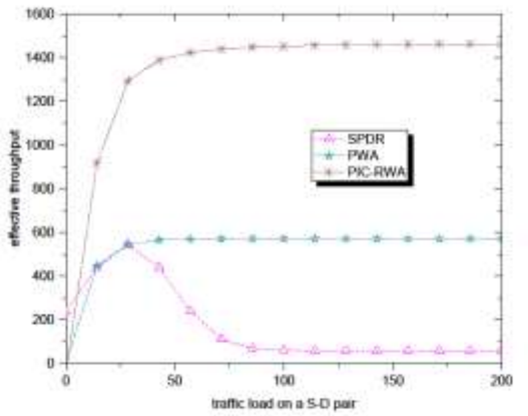


**Figure 13: Effective throughput per S-D pair as a function of offered load**

With regards to the utilization, we observe from Figure 13 that for light to moderate traffic loads, the network is generally underutilized.

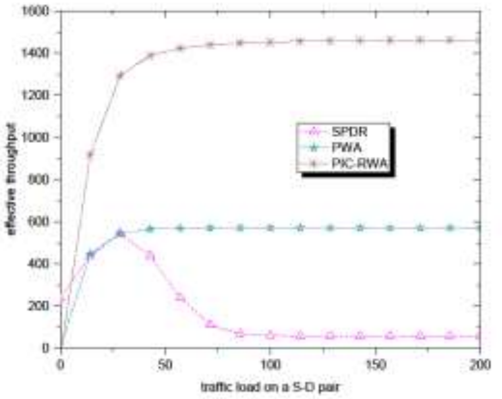


**Figure 13: Effective throughput per S-D pair as a function of offered load**

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 are able to reach their destination.

Performance comparisons of the proposed scheme with regards to both the effective throughput and utilization are shown in Figures 13 and 14 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 also the burst arrival rate to each S-D pair is the same. In Figure 13, 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 14 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 are able to reach their destination.

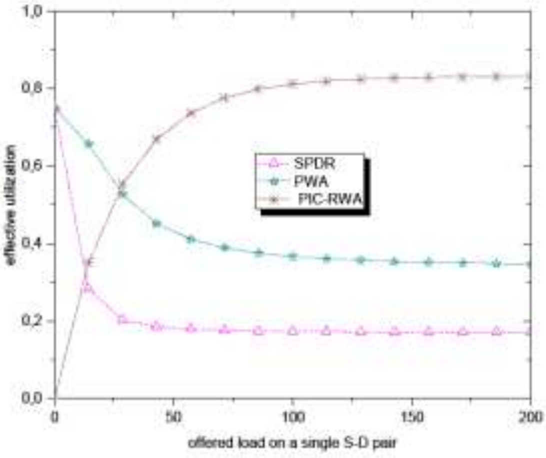


**Figure 14: Effective utilization per S-D pair as a function of offered load**

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

## Conclusion

In this paper, we proposed a prioritized (indexed) cooperative-based routing and wavelength assignment (PIC-RWA) scheme that is geared towards reducing both contention and wavelength congestion partly because of deflected bursts being relayed to other alternate routes. For the scheme to achieve its target goal(s), for each newly assembled data burst at an ingress node, all possible candidate shortest hop routes between the source and destination as well as adjacent nodes are computed and then ordered according to individual their UI and SI values so that the most optimal route is ultimately chosen. Simulation results have shown that the scheme, by comparison, does improve overall network performance in terms of improved effective resource utilization.

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