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A controlled deflection routing and wavelength assignment based scheme in Optical Burst Switched (OBS) networks

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Abstract: Heterogeneous IoT-enabled networks generally accommodate both jitter tolerant and intolerant traffic. Optical Burst Switched (OBS) backbone networks handle the resultant volumes of such traffic by transmitting it in huge size chunks called bursts. Because of the lack of or limited buffering capabilities within the core network, burst contentions may frequently occur and thus affect overall supportable quality of service (QoS). Burst contention(s) in the core network is generally characterized by frequent burst losses as well as differential delays especially when traffic levels surge. Burst contention can be resolved in the core network by way of partial buffering using fiber delay lines (FDLs), wavelength conversion using wavelength converters (WCs) or deflection routing. In this paper, we assume that burst contention is resolved by way of deflecting contending bursts to other less congested paths even though this may lead to differential delays incurred by bursts as they traverse the network. This will contribute to undesirable jitter that may ultimately compromise overall QoS. Noting that jitter is mostly caused by deflection routing which itself is a result of poor wavelength and routing assigning, the paper proposes a controlled deflection routing (CDR) and wavelength assignment based scheme that allows the deflection of bursts to alternate paths only after controller buffer preset thresholds are surpassed. In this way, bursts (or burst fragments) intended for a common destination are always most likely to be routed on the same or least cost path end-to-end. We describe the scheme as well as compare its performance to other existing approaches. Overall, both analytical and simulation results show that the proposed scheme does lower both congestion (on deflection routes) as well as jitter, thus also improving throughput as well as avoiding congestion on deflection paths.

Keywords: contention; contention resolution; deflection route; deflection routing; jitter; Optical Burst Switching.

1 Introduction

In the Optical Burst Switched (OBS) domain, primary concerns are in combating congestion as well as contention as bursts traverse the core network. The two are interdependent and thus managing them is key towards the provisioning of consistent quality of service (QoS) for the various services and applications. QoS metrics such burst end-to-end latencies as well as blocking probability will degrade on the onset of contention and/or congestion. With regards to an OBS network, various types of congestion e.g., nodal, control processing unit (CPU) and path may occur. Nodal congestion occurs when incident traffic overwhelms the serving node. CPU congestion arises as a result of too many computations that jam the main CPU scheduler. Path or link congestion is caused by excessive traffic attempting to traverse the same path. In the context of OBS networks, congestion thus can be caused by several factors such as contention; uneven distribution of traffic leading to localized traffic overload, as well as improper provisioning of available resources such as is in the case of routing and wavelength assignment (RWA). The presence of buffering capabilities at edge nodes makes it easy to combat edge congestion. Path congestion can be alleviated by way of dimensioning the available network resources such as wavelengths and links such that traffic is uniformly distributed throughout the network [1, 2]. Overall, appropriate measures as well as mechanisms must be implemented in a congested network so as to contend with a temporary increase in demand for network resources during congestion periods. Such mechanisms can be implemented either inside the network (i.e., at OBS switches) or at the source nodes where bursts originate [2].

It is noted that contention will always occur at interior nodes when more than one data burst utilizing the same wavelength overlap in time at the same single output port.

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Because of the bufferless nature of such networks in their interior, different approaches are adopted to alleviate as well as combat contention. Primarily, the contention resolution mechanisms can be implemented at space, wavelength, or time domains. At wavelength domain level, wavelength converters (WCs) may be used occasionally to resolve the contention by translating one of the contending wavelengths to a different value. In so doing, the network's performance improves. In the time domain, contention resolution was implanted or affected by introducing fiber delay lines (FDLs) to temporarily delay one or more of the contending bursts until such time that the output port becomes available. In the space domain, deflection routing (DR) is introduced to resolve any contention occurrences in which one of the contending bursts can be deflected to an alternate port as well as route. In this way, both congestion as well as contention are distributed to other routes rather than being concentrated on a single one and in the process the network's general performance improves. Nevertheless, it should be noted that DR also has several drawbacks, notably that it can accelerate contention as well as 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. Furthermore, 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 DR itself must be controlled [3–5].

It is on the strength of the earlier cited weakness that in this paper, we propose a controllable DR scheme which couples with a simple wavelength and routing assignment (WRA) algorithm to enhance overall network performance, by minimizing both contention and congestion. The scheme attempts as much as possible to deflect either of the contending bursts to paths that have been chosen based on the minimization of performance measures such as delay and blocking. Furthermore, the scheme also aims at controlling deflection traffic by way of selective path routing upon congestion onset. It is backed by a very simplified distributed RWA approach that ensures minimal contention in the primary (original) chosen route(s). Notably, a distinct feature of the proposed scheme is that it allows the deflected bursts to traverse further via deflection routes optimized for improved performance in terms of delay and blocking. The candidate deflection routes are themselves dynamically classified according to key QoS constraints (e.g., blocking and delay) they can support [6].

Summarily, the contributions of this paper are as follows:

(1) We propose and describe a controlled deflection routing (CDR) scheme which couples with a fairly simplified RWA approach to ensure minimization of both differential delays and blocking on deflection paths. In the process, the deflected traffic does not compromise the QoS of already existing connections, if any, on these two paths.
(2) Of the chosen available candidate deflection routes, we further propose a fast-randomized least cost algorithm for selecting the two possible routes that closely satisfy both delay and blocking constraints as the original path.
(3) A Markov type queuing model comprising a common queue feeding to two servers (representing the system) is analyzed. We provide expressions for computing system states, as well as a heuristic formula for computing the bursts waiting (delay) times in the system.

The rest of the paper is outlined as follows: In the next section, we provide an overview of some related works with a focus on QoS-aware contention resolution approaches. The focused QoS metrics are mainly end-to-end delays and blocking probabilities. This is followed by a brief elaboration on bufferless OBS networks and contention in such networks. The proposed CDR scheme is presented in more detail in section four. In section five, we model the controllable DR queuing model. Section six presents both analytical as well as simulation results pertaining to the proposed scheme. Finally, conclusions are drawn in the last section.

2 Related work

This section reviews a few works regarding deflection contention resolution QoS-aware approaches. Primarily, a given contention resolution mechanism can be implemented as a hybrid combination of one or more of traditional approaches such as buffering using FDLs, wavelength conversion, burst segmentation, or DR. Implementing the buffering and wavelength approaches will require the incorporation of extra hardware in the form of FDLs and WCs in the interior nodes, thus escalating overall network capital expenditure (CAPEX). The segmentation approach will require modification of existing burstification algorithms at ingress nodes. Key to this approach would be the scheduling of the segmented data bursts such that contention can be controlled but without compromising channel utilization. Various literatures have explored the effectiveness of the segmentation approach in controlling contention as well as its effects of overall QoS in the core network. The work in [7] proposes combined burst segmentation and scheduling approach in which the Best Fit Void Filling (BFVF) algorithm is implanted. With this algorithm, the next data burst is scheduled on the channel that offers the maximum void utilization factor. When contentions occur at core nodes, selective discarding of overlapping segments is carried out without necessarily discarding the entire contending bursts. In that way, the overall packet loss probabilities are lowered and at the same time channel utilization as well as multiplexing improve. The scheme, however, does not make a provision for retransmitting the discarded data burst segments. The authors in [8] indirectly extend this work by introducing a less similar scheme in which the truncated sections of the segmented burst are retransmitted. The scheme carefully takes into consideration the possible overload conditions that may occur in the retransmission paths. Hence, the scheme relies on a computed retransmission probability control parameter to decide on whether the entire burst should be retransmitted or not. Overall, the approach does lead to increased path blocking but low byte loss probabilities. The overall performance of the schemes proposed in [7] and [8] can be further improved by appropriately modeling the incident traffic at both ingress and core nodes. The work in [9] provides a basis for modeling segmented bursts. In this regard, the author focuses on the head dropping contention resolution approach being implemented for various service disciplines. In a nutshell, the work does not consider retransmission of the discarded segments. Because segmentation-based contention resolution approaches rely on selectively discarding contending sections of the segmented bursts, it is however necessary that the hop count as well as fairness to all applications be taken into consideration. In this regard, the work in [10] introduces a contention resolution approach that considers the effective utilization as well as throughput for individual source–destination pairs. The approach is a combination of the burst segmentation and Least Remaining Hop-count First (LRHF) scheme. The combined scheme implements intermediate buffering for contending data bursts that have been traversed several hops in the network. The results obtained show that the scheme performs well in terms of key QoS metrics such as network throughput, data burst loss probabilities as well as load balancing.

DR contention resolution approaches are relatively practical, cost effective as well as scalable, hence in this section we focus on deflection route choice algorithms. We once more emphasize that the key towards successful operation of an OBS network with consistent as well as guaranteed QoS is to ensure that end-to-end delays as well as loss probabilities incurred by the bursts are within acceptable bounds. Differential delays incurred by multiple bursts accommodating a particular application or service may result in excessive jitter, so is high burst losses may result in the connection terminating. Key OBS network operations that influence these two key QoS parameters may include burstification, wavelength reservation, scheduling, and contention/congestion resolution approaches. Hence, the review on related works unavoidably incorporates some of these key operations.

Contention DR resolution approaches can be categorized as either; *(i) limited DR* or (*ii*) *performance constraints based*.

Limited DR-based contention resolution limits the number and frequency of deflections during heavy network traffic periods in order to prevent any possible network instabilities that may lead to overall performance degradation [11]. This can be implemented by setting dynamic burst deflection probabilities which will generally be lowered when network traffic loads are high [12]. Alternatively, a few wavelengths on each link can be reserved exclusively for primary bursts. Priority approaches in which primary bursts can pre-empt reservations for deflected bursts have also been explored [13].

The performance of a constraints-based approach selects the deflection path according to some certain performance metrics such as blocking, latency, utilization, etc., This is to ensure that congestion is avoided or minimized. For an example, a path may be selected based on the minimization of a set of metrics such as remaining number of hops and blocking. Overall, schemes in this category may perform relatively well in terms of blocking probabilities at the expense of additional delays [14].

The work presented in [15] explores the possible impact of a deflection path selection criterion on all other existing connection paths. The authors carry out an analysis of the extent of contention among various burst streams as well as interaction between the route selection and traffic load balance. In selecting a candidate deflection route, they employ “a maximum-efficiency-first multi-path selection strategy” which only considers blocking probability as well as overall link utilization. They however do not take extra incurred delays by the longer routes into account and hence such a scheme does contribute to differential delays to the individual bursts.

The authors in [16] propose a class-based contention resolution scheme which incorporates composite burst assembling at the edge node followed by selective burst segmentation and DR in the core network. During assembly, the highest priority data packets are placed in the middle while low priority packets tail and head the burst. When contention is encountered, either the tail or head ends are likely to be discarded or deflected. In short, the scheme prioritizes the high priority (HP) segments of the bursts. Overall, in terms of performance, the scheme favors the HP segments in terms of both blocking and end-to-end delays. It does not take into consideration the impact of the deflected burst(s) on deflection parts. A more or less similar burst segmentation-based contention resolution scheme was proposed earlier in [17] in which, a portion of the burst which overlaps with another burst is segmented instead of dropping the entire burst. The remaining segment will be transmitted on the original path or deflected on a single alternate path. The drawback with this scheme is that whereas it enhances packet delivery ratios, it however contributes to increased latencies to the discarded segments as they will have to be retransmitted.

A routing scheme called the Shortest Path Prioritized Random Deflection Routing (SP-PRDR) is presented in [18]. It primarily aims at lowering blocking probabilities for all input traffic load ranges, topologies and routing matrices while only using acquired network's resources state information. Their results show that the SP-PRDR scheme does significantly lower burst blocking probabilities with not much impact on end-to-end latencies. They however do not address the differential delays incurred in the network as a result of the deflections.

A Neural network (NN) based contention resolution DR approach is proposed in [19]. The authors develop a Q-Learning reinforcement algorithm that assists the nodes in making intelligent deflection decisions. The proposed algorithm scales well for larger networks because its complexity depends on the node degree rather than the network size. The authors in [20] and [21] use a Markov model to estimate the blocking probabilities of various traffic service classes, and then later, model the RWA as a bi-objective Integer Linear Programming (ILP) problem with an objective of minimizing the number of hops to be traversed by bursts for any given set of node pairs. The latter is solved using a Differential Evolution (DE) algorithm-based approach. In both cases, the focus was only on burst blocking probabilities and no attention was paid to differential delays.

3 Deflection routing contention resolution

The OBS approach is rapidly becoming the backbone network solution for future generation networks; this is attributed to such a network's higher resources utilization, flexibility, as well as ultra-high bandwidth capacities both at transmission and switching levels. At the ingress node, multiple data packets are assembled together to form a super-sized packet called a data burst. The core nodes in an OBS network are bufferless and hence the formed huge data bursts cannot be temporarily stored prior to switching in them. Rather, the data-burst transmission is delayed by an offset time (t_{offset}) relative to its control packet (BCP), and later follows the burst control packet (BCP) without waiting for an acknowledgment for resource reservation confirmation. Thus, a burst may be lost at an intermediate node due to contention, i.e., when two or more data bursts contend for the same output port in which case, they overlap both in time and wavelength. The burst losses due to contention are one of the key issues hindering the realization of OBS backbone networks that can support guaranteed QoS. Contention can be resolved by way of DR in which the contending data burst(s) is deflected to alternate routes. These have to be carefully chosen so as not to degrade the overall network performance. By nature, DR assists in balancing the traffic traversing the entire network. The deflection multi-path routing and load balancing techniques can be effective in distributing the traffic over all links of the network, provided that all ingress nodes have adequate network state information, such as traffic situations in the various parts of the network. Accordingly, to fully utilize the potential of DR, each core node has to periodically receive information about the utilization of other links across the network. Otherwise, simply forwarding contending bursts to idle ports may in some situations even increase contentions.

Figure 1 illustrates DR in OBS networks. When a core node x_i receives a BCP, it extracts the routing information contained in the BCP and uses it to pre-configure the desired output port before the actual data burst arrival. In this case, it has t_{offset} time allowance to locate and pre-configure the port on the outgoing link $l_i, i = 1, m$. We consider a bufferless network comprising $N = \{x_1, x_2, \ldots, x_n\}$ sets of nodes. Node x_i routes data bursts flows f_1 and f_2 that are destined for egress nodes x_{d1} and x_{d2} respectively. Using the shortest path first, both data bursts from flows f_1, f_2 should be forwarded to the intermediate node x_j via link l_0. In this case, both will contend for the output port of l_0. If no contention resolution scheme is implemented, the data burst from f_1 is forwarded to x_j and ultimately to the destination x_{d1} via l_0 whilst the other data burst is discarded. However, if a DR is implemented as the contention resolution scheme, the data burst from flow f_2 is accommodated on an alternate deflection link $l \in \Im \setminus \{l_0\}$, where $\Im$ denotes a set of all available outgoing links from x_i. The available links must be carefully chosen such that the deflected data burst does not incur increased delays and blocking as it traverses further to its ultimate destination x_{d2}. Another issue that needs particular attention is the interaction of DR with offset-based signaling scheme.

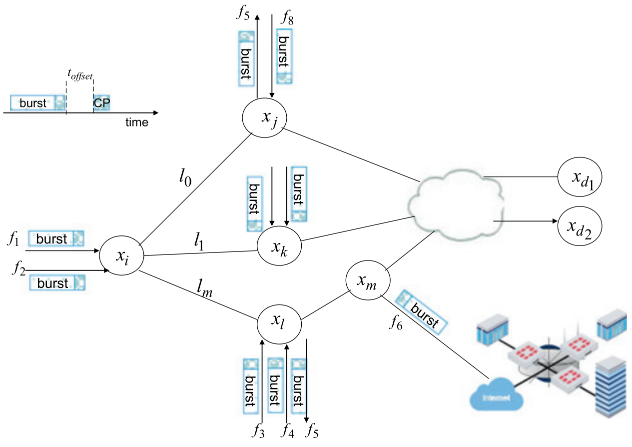
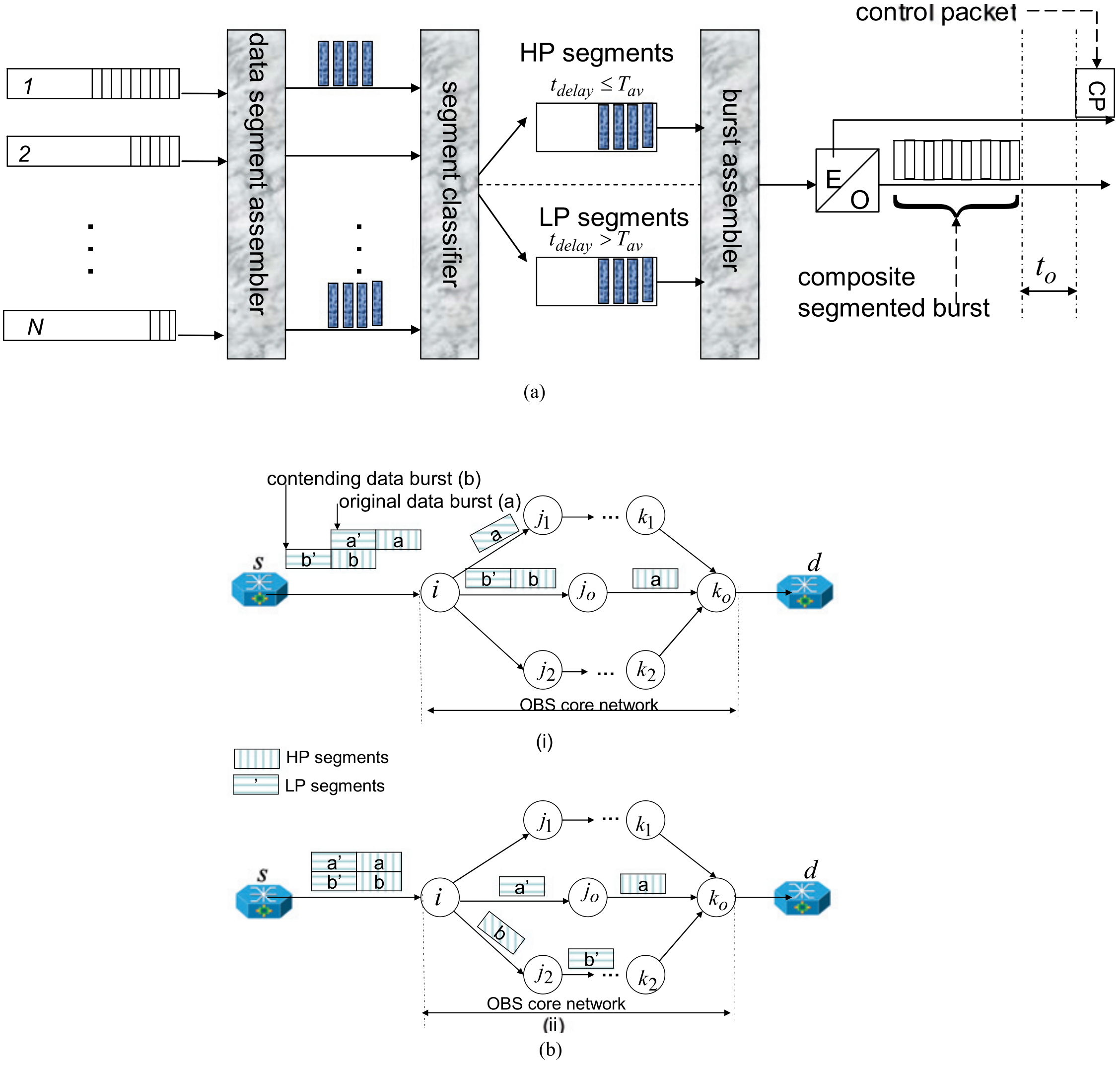


Figure 1: Network with bufferless interior nodes.

When an intermediate node decides to deflect a burst on a particular route, it has to check if this will increase the overall end-to-end delay (as well as blocking) or not.

An example illustration of DR contention resolution is illustrated by Figure 2. Figure 2 (a) summarizes the segment burstification algorithm which initially assembles equal sized class-based data segments. The classification is largely determined according to time delay constraints for the individual data packets. The overall burst assembly process model is both time and size constrained. The HP segments may not be delayed by $T_1^{\max}$whilst the low priority class (LP) segments may tolerate up to $T_2^{\max}$. The assembled segmented burst itself should be of minimum acceptable size $S_{\min} \leq S(t) \leq S_{\max}$, before it is scheduled. Whereas the algorithm always prioritizes the HP segments,



(a)

(i)

(ii)

(b)

Figure 2: (a). An example of segment burstification. (b). DR contention resolution.

however, upon expiry of their delay time constraint, an LP segment class block will be padded in order to satisfy the segmented burst size constraint $S_{\min}$, In practice, a void between the two class segment blocks will facilitate easy segmentation in the core network should contention be encountered. Figure 2 (b) illustrates contention resolution by way of DR. It is noted that the aim of the segmented burst approach is to separate any contending segment class block and deflect it to a non-congested alternate path in the core network rather than discarding it completely [22, 23].

Figure 3 provides a flowchart that summarizes the traditional DR contention resolution scheme. In practical implementation, the ingress node incorporates a DR information database (DRIB). The DRIB stores key management information both at the routing and optical layers of the network. The ingress node periodically dispatches special control packets for the purpose of acquiring control information necessary for the entire OBS network to carryout operation, supervisory, administration, and maintenance (OSAM) functions. These functions also aid the DRIB in furnishing precision information to assist in deflection route choices. These control packets are not associated individually with data bursts. Whenever network status changes, the management database should be updated accordingly. In this case, associated OSAM control packets are generated and dispatched on a dedicated control channel normally referred to as an optical supervisory channel (OSC) that interconnects with all network nodes.

In that way, each core (intermediate) node is periodically updated on general network status, performance in terms of burst loss rates due to contention and possibly congestion, as well as remainder hop counts for each burst-mode connection to intended egress node. As narrated before, the BCPs are those that are coupled individually with each data burst. Each BCP ferries information regarding the number of remaining hops to be traversed by the burst, residual offset timing, as well as burst length. The information is used to schedule required resources for the burst at the next node ahead of its actual arrival. When it is determined that a burst is heading for contention with another burst, the DR contention resolution mechanism protocol is invoked, and it utilizes information extracted from the associated BCP as well as DRIB to try to deflect the contending data burst appropriately. The affected intermediate node already has the relevant attributes about its input/output ports including contention status and hop counts from the OSAM control packets. Furthermore, an intermediate node can also request an OSAM control packet from the egress node when necessary. Ideally, updated assessment as well as measurement about burst contentions is needed at all the nodes in the network for the DR contention resolution algorithms to perform well. Further illustrated in Figure 3, is the mechanism for signaling contention occurrences and updating the burst contention status and statistics. Each ingress node receives updates about the burst congestion status along the primary and alternate candidate routes. These updates are signaled in the form of NACK, and ACKs messages. In practice, NACKs from primary and alternate routes are distinguished from each other, as well as treated separately.

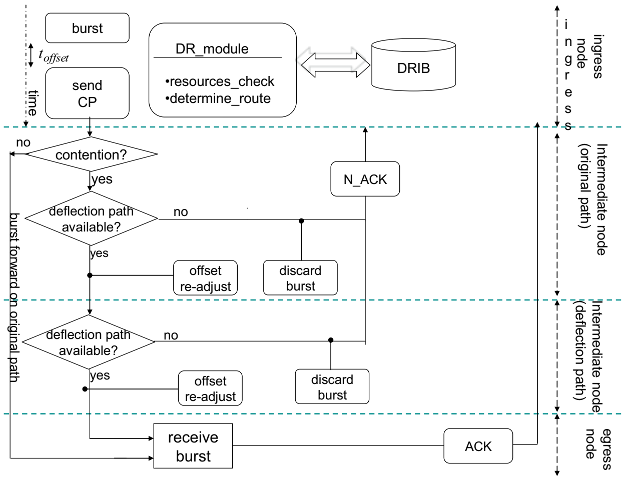


Figure 3: Contention and burst deflection.

4 Proposed controllable deflection routing (CDR) scheme

We commence the section by describing the proposed scheme. Figure 4 depicts a generalized architecture of an OBS switch which comprises several input and output wavelength division multiplexed (WDM) link ports.

Wavelength light paths from input fibers are demultiplexed prior to switching to the desired output ports. In the event of contention, one of the contending data bursts is deflected to an alternate route. Periodic global re-optimizing of candidate deflection routes based on the most recently exchanged contention as well as congestion status updates from other nodes is necessary.

In the event that the network management system reports contention as well as wavelength congestion or its imminence on the deflected route, the contending burst may be converted to any other available wavelength by a WC. This updating interval is carefully selected in accordance with the computing power capabilities of the node so as not to cause nodal computational congestion. As can be

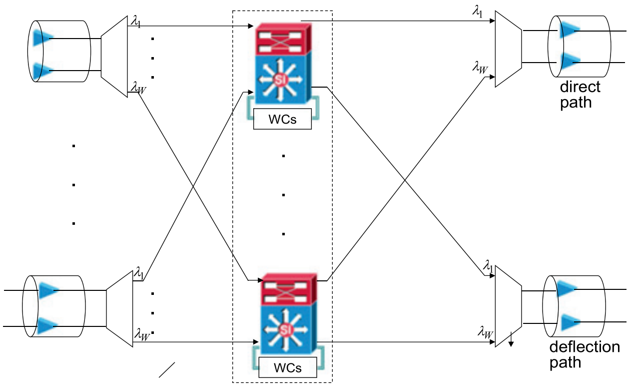


Figure 4: Switch architecture with wavelength converters (WCs).

seen in Figure 4, the switch fabric can only accommodate a limited number of both optical links as well as wavelengths.

The number of input/output switch pairs tally with the number of shared WCs. A key feature of this switch architecture is that the choice as well as usage of deflection paths is controlled and by all means, it will always strive to route bursts intended for a common receiver/destination pair on the same (original intended) path. In the event that contention has occurred and as a result, routing of both data bursts on the original path no longer possible, one of the contending burst's wavelength is converted or, worst case it is deflected on to a selected least cost alternative route (chosen in terms of minimal delay and blocking metrics). The scenario just described is further represented by the queuing model of Figure 5.

All arriving bursts are served on a FCFS service discipline policy. Path server #1 queue represents a deflection path that offers minimal QoS degradation in terms of blocking and delay. A contending burst will be dispatched to server one queue representing the first-choice deflection path out of the two, only if the controller buffer's capacity has exceeded a threshold state q_1. Similarly, path server #2 represents the second-choice deflection path that will be utilized only when the controller buffer's threshold has exceeded q_2. Otherwise the original path will always be preferred. Neither of the two deflection paths can be expected to consistently meet its QoS expectations, hence in general, we define, α as a given path's rate of exiting its QoS bounds, and similarly β would be the rate at restoring it to within bounds. This transition state is shown in Figure 5 (b).

In addition, also key to alleviating both contention and wavelength congestion is affective RWA.

We propose a simplified RWA method which evenly distributes the number of available wavelengths on all fibers as well as links. A network routing map (NRM) together with simplex signaling are assumed. Each node furnishes as well as advertises the following static information to the NRM:

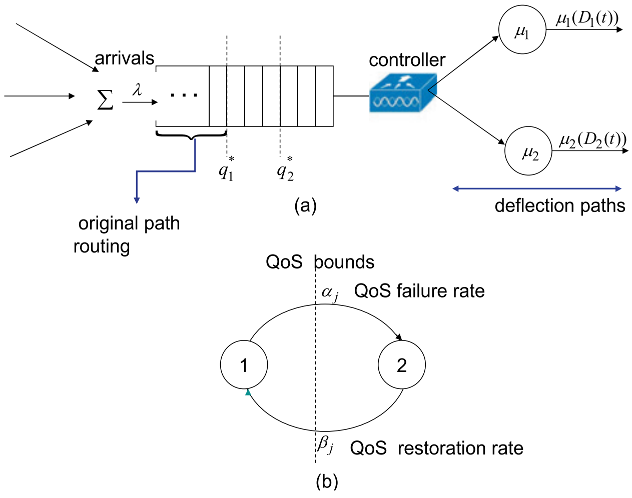


Figure 5: Queuing model.

- candidate routes as well as overall network resources state to all destinations as example illustrated in Figure 6 (a).
- sum of available links as well as fibers (wavelengths).
- Each node also provides end-to-end link occupancy states for all possible links it serves to all other destinations.

An example individual fiber wavelength occupancy at each node is also illustrated in Figure 6 (b). All this information is dynamic hence it has to be updated periodically at an interval ΔT_{update} on the NRM.

The concatenated wavelength occupancy state can be represented by O such that:

$$O = (t, st) \tag{1}$$

where t, is the start time and st is the state of the slot.

A single wavelength's occupancy state can be represented by a sequence vector of slots as follows:

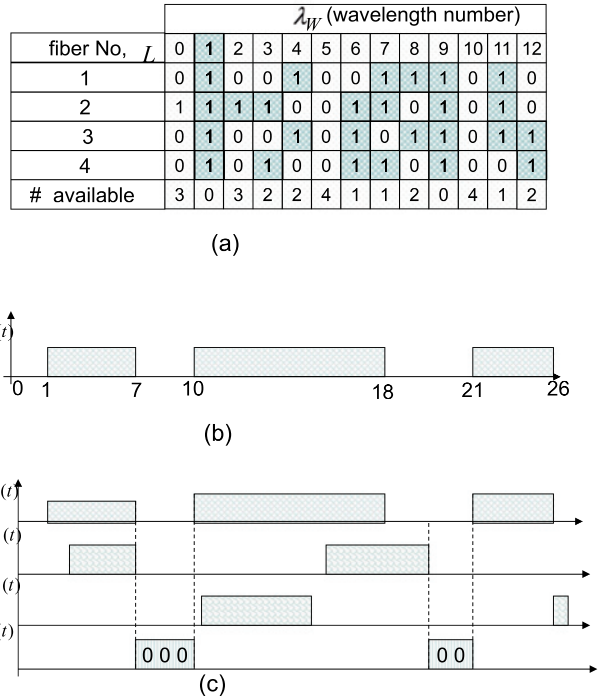
$$O_\lambda(t) = [O_{1,}, O_2, \ldots, O_n] \tag{2}$$

The state occupancy of concatenated links (candidate light path) can be defined as:

$$O_L(t) = [O_{\lambda_1}(t) \oplus O_{\lambda_2}(t) \oplus, \ldots, \oplus O_{\lambda W}(t)] \tag{3}$$

where the operation $\oplus$ denotes a search algorithm for free wavelengths along the links.

We can formulate the key DR problem primarily as a function of the node configuration, general network topology as well as a set of QoS related attributes such as node and link resources [24].



fiber No, L	λ_W (wavelength number)												
	0	1	2	3	4	5	6	7	8	9	10	11	12
1	0	1	0	0	1	0	0	1	1	1	0	1	0
2	1	1	1	1	0	0	1	1	0	1	0	1	0
3	0	1	0	0	1	0	1	0	1	1	0	1	1
4	0	1	0	1	0	0	1	1	0	1	0	0	1
# available	3	0	3	2	2	4	1	1	2	0	4	1	2

Figure 6: Wavelength management; (a). An example of a link state data structure, (b) An example of a single wavelength occupancy state sequence, (c). An example of a concatenated wavelength occupancy state.

If the physical network is denoted as $G(L, N)$, where N is the number of nodes comprising it and L is the set of links interconnecting the nodes.

Each link $L_{i,j}$ has a total of W_{ij} wavelengths each with capacity C.

Each network node $n, (n = 1, N)$ has $P_n^{in}(t)$ and $P_n^{out}(t)$ ports. We define a source (s) and a destination (d) pair as well as an associated burst arrival rate $\lambda_{i,j}^{sd} \in \Lambda$, at the switch queue. We also define $\lambda_{s_k} d_k$ to represent the average flow of bursts belonging to class k type traffic. We thus can define:

$$x_{ij} = \begin{cases} 1, & \text{if deflection route includes, link } L_{i,j} \\ 0, & \text{otherwise} \end{cases} \quad i, j = 1, N, i \neq j \tag{4}$$

Since one light path can be set up at each node we thus have:

$$\sum_{\Lambda, j \in N} \mathrm{x}_{\mathrm{ij}} \le P_i^{out}(t), \quad \sum_{\Lambda, i \in N} \mathrm{x}_{\mathrm{ij}} \le P_j^{in}(t) \tag{5}$$

Thus, the traffic demand $\lambda_{s_k} d_k$ deflected from node i to j is:

$$\lambda_{i,j}^{s_k, d_k} \in \{0, \lambda_{s_k, d_k}\} \quad \forall_{\ \mathrm{i,j}} \in N \tag{6}$$

The aggregated one-way flow from node i to j associated with the k traffic demand is:

$$\lambda_{ij} = \sum_{s,d} \lambda_{ij}^{sd} + \lambda_{s_k d_k} \quad \forall_{i,j} \in N \tag{7}$$

Traffic from node i to j may not exceed the maximum capacity C hence we have:

$$\lambda_{ij} \le W_{i,j} C \quad \forall_{i,j} \in N \tag{8}$$

If the same link $L_{i,j}$ is not associated with the k-the traffic type flow, then the previous equation becomes:

$$\lambda_{ij}^{s_k d_k} \le x_{ij} \lambda_{s_k d_k} \quad \forall_{i,j} \in N \tag{9}$$

Finally, at each node the flow conservation constraint becomes:

$$\sum_i x_{ij} - \sum_j x_{ji} = \begin{cases} 1, i = s_k \\ -1, i = d_k \\ 0, \text{otherwise} \end{cases} \quad \forall_{s_k, d_k, i} \in N \tag{10}$$

Eventually, if we let $D = \{D_{ij}\}$ represent the distance matrix as well as delay between nodes i and j we can thus summarize our key objective function as follows:

$$\text{Min } \gamma_{\mathrm{d}} \sum_{ij} x_{ij} D_{ij} + \gamma_b \left[\log\left[1 - \prod\nolimits_{i,j} (1 - x_{ij} b_{ij})\right]\right] \tag{11}$$

Where, γ_d and γ_b are the delay and blocking weights respectively. Collectively, they are designated as a deflection path link cost factor.

$$c = f(\gamma_d, \gamma_b) \tag{12}$$

The key steps of the proposed CDR algorithm are summarized as follows:

i. Ingress (source) node dispatches a BCP requesting an end-to-end connection to a specified egress (destination) node.
ii. the intermediate node processes the BCP together with those from other sources. If resources are available of the primary route (and is contention free), the burst will be accepted.
iii. However, if contention is detected i.e. simultaneous requests for the same output ports and wavelengths, by two or more BCPs then the contention is resolved before actual burst arrival in one of the following ways: -
    a. If the node is the sender, its BCP is discarded and retransmission is ordered at a later time.
    b. The remaining bursts can either be assigned to the primary route, deflected to an alternate path, or in the worst case, be discarded. This is done according to the set of rules in step iii:
iv. *assigned to the original path*: There exists two or more contending bursts all n transit. The node's controller is

in state $q < q_1^*$, and there are enough free wavelengths to accommodate all the contending bursts. Their initial wavelengths will be shifted accordingly by the WCs.

deflected to path #1: The node's controller is in state, $q_1^* \le q < q_2^*$.

deflected to path #2: The node's controller is in state, $q_2^* \le q \le \infty$.

Note that the threshold values q_1^* and q_2^* are set by taking into account the delay and blocking weights in Eq. (11).

5 Queuing model analysis

In this section, we analyze the queuing model provided in Figure 5. We recall that our objective is to minimize both jitter and blocking probability by routing bursts originating from a given source to a destination on a single path. To simplify the model, we will assume a single dispatcher queue and K path servers, each with service rates $\mu_j, j = \overline{1, K}$. Bursts arrive at a rate λ. Each server $j$represents an onward path with its own fixed QoS bounds i.e., jitter and blocking. When busy, the path exits this bound at a rate α_j and once exited, it tries to revert (restore) to this bound at a rate β_j. Choice of the chosen deflecting paths is dependent on the fixed queue thresholds q_1, q_2.

System states at any arbitrary time are [25]:

$$D_j(t) = \begin{cases} 0, \text{ original path in use or system idle} \\ 1, \text{ deflction route is busy} \\ 2, \text{ deflection route is busy failing to meet QoS} \end{cases} \quad j = \overline{1, K} \tag{13}$$

We can define a state space of the path servers as;

$$E_D = \left\{ (d_1, d_2) ; \left| \begin{array}{l} d_j \in \langle 0, 1, 2 \rangle, \ 0 \le q \le q_1 \\ d_1 \in \langle 1,2 \rangle, d_2 \in \langle 0, 1, 2 \rangle, \ q_1 \le q \le q_2 - 1 \\ d_1 \in \langle 1,2 \rangle, d_2 \in \langle 0, 1, 2 \rangle, \ (d_1, d_2) \ne (2, 0), q_2 \le q \le \infty \end{array} \right. \right\} \tag{14}$$

From which we can re-define a state space as well as a random process respectively as:

$$E = \{x = (q, \mathbf{d}) ; q \in N_o, \ \mathbf{d} = (d_1 d_2) \in E_D\} \tag{15}$$

Under stationary conditions, we also have;

$$\rho = \lambda \Big/ \sum_{j=1}^{K} \beta_j \mu_j \left(\alpha_j + \beta_j\right)^{-1} < 1 \tag{16}$$

The utilization of each deflection path is:

$$U = 1 - \pi_{(0,0,0)} \tag{17}$$

where $\pi_{(0,0,0)}$ denotes an empty state space.

6 Analysis and simulation

In both our numerical as well as simulation performance analysis, we assumed the following:

L–fixed data burst size 600 *MB*, and a BCP offset time of 0.4 msec. Each link has a capacity $C = 6$ Mbps.

λ–Burst generation rate of 120/s. The network updating interval is fixed throughout the simulation runs. When a connection request arrives at a node, a wavelength is assigned along the least cost path:

$$c_o \le \frac{\alpha_i c_{1,2} + \beta_1 c_{1,1}}{\beta_1 \mu_1} \le \frac{\alpha_2 c_{2,2} + \beta_1 c_{2,1}}{\beta_2 \mu_2} \tag{18}$$

The evaluation is carried out on a multi-node network using OMNET++ (version 5.4).

In Figure 7, node 0 is the source (s) whilst node 12 is the destination (d). Source routing using the random shortest path first algorithm is assumed. An Edge node configuration is shown in Figure 8.

We further make additional assumptions as follows:

- At the source node, all bursts are categorized according to QoS constraints e.g., blocking and delay.
- The various links constituting the network vary in lengths. They are also bidirectional with each fiber comprising 16 wavelengths, two of which are dedicated for signaling purposes.
- Besides the original path, only two other deflection paths are available between this node and the destination.

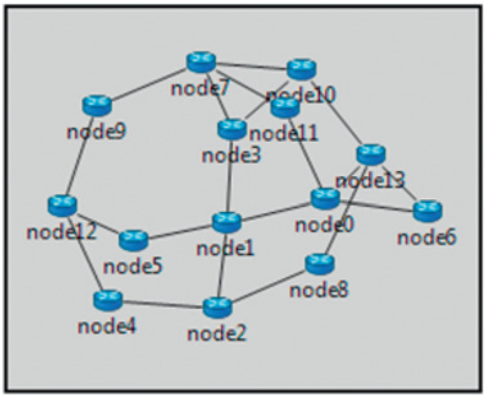


Figure 7: Network model.

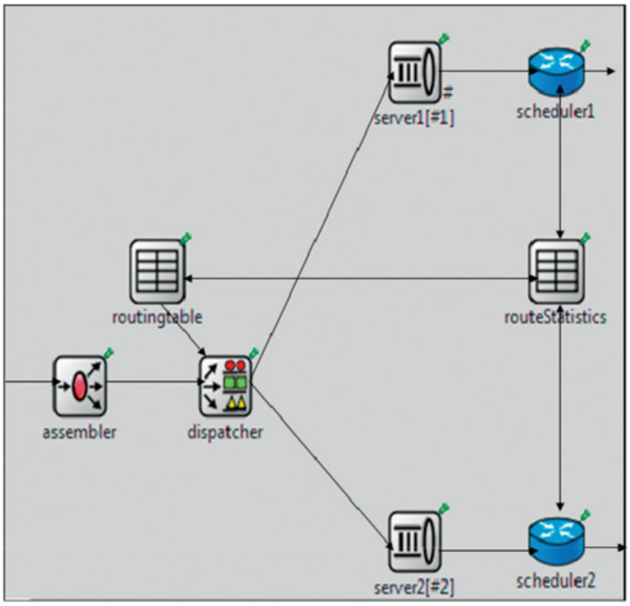


Figure 8: Edge node configuration.

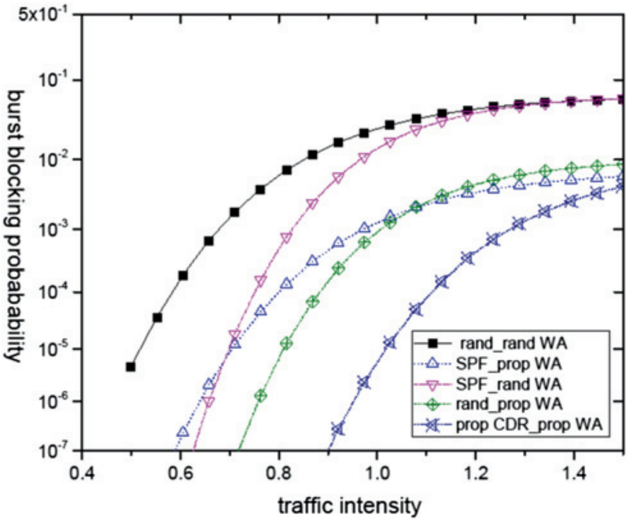


Figure 9: End-to-end burst loss probability versus load.

This means the original path is preferred before deflection to *path* #1 and *path* #2 respectively as it has the lowest cost.

We first analyze the performance of the proposed CDR and WA (prop CDR_prop WA), scheme in terms of burst loss probabilities.

In so doing, we compare it with other schemes such as:

- CDR with random WA (prop CDR_rand WA,), in which the wavelengths are randomly assigned.
- shortest path first together with random WA (SPF_rand WA).
- random path and random WA (rand_rand WA).
- SPF and proposed WA (SPF_prop WA.

Figure 9 shows several plots of the P_B as a function of varying traffic load. From this graph, it is observed that the proposed CDR as well as the proposed wavelength assignment (prop CDR_prop WA) outperforms the rest of the schemes.

Random routing coupled with the proposed WA (rand_prop WA) also shows fairly good performance as it tends to distribute traffic among the available routes. It is generally concluded that a combination of CDR and the proposed WA will reduce end-to-end blocking probabilities.

Figure 10 shows how path blocking varies as a function of the aggregate number of wavelengths available on the path. The traffic load is maintained at 100%. An increase in the number of fibers per path results in reduced blocking. Noticeable is that the traffic is evenly distributed within the fibers and the traffic also uniformly spread, hence this leads to reduced blockings. We also explore the effect of increasing the number of wavelengths on blocking. Once again, the Poisson arrival process is used in which each fiber's traffic load is set to 100%. The simulation scenario this time is repeated with three randomly chosen sets of ingress and egress node pairs.

Furthermore, by comparison, it can be observed from Figure 11 that the proposed scheme performs relatively much better when the number of wavelengths is increased, and at the same time the available resources are utilized uniformly and rationally.

We gradually increase the bursts arrival rate from 0 to more than 100% so that the controller queue is always above the q_2 threshold value and by so doing it is noted that

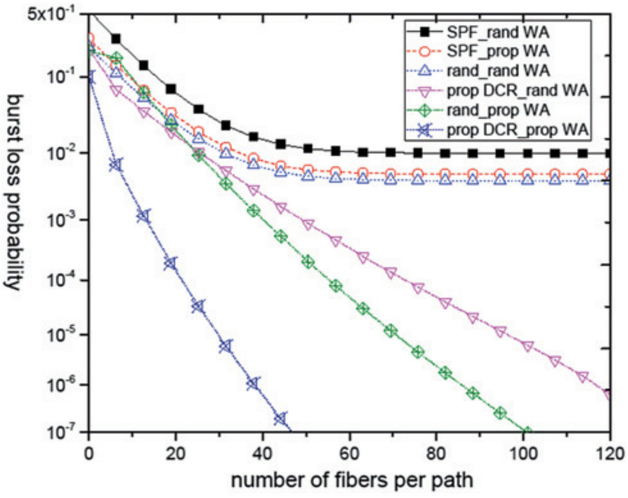


Figure 10: Loss probability as a function of number of fibers per path.

deflection does reduce blocking, even though it may propagate or trigger congestion/contentions in the deflected routes. From Figure 12, it is observed that by comparison, the proposed scheme is outperformed by the SPF_propRWA scheme at very high loads. As expected, the number of deflections increases almost exponentially for all the schemes. It may thus be necessary to regulate the volumes of deflected traffic. Figure 13 plots the performance of the various schemes (in terms of end-to-end delays) as a function of total number of nodes traversed. The controlled scheme performs comparably better at high traffic volumes as it regulates the actual numbers deflected, e.g. some bursts are discarded.

In this case we compute the delays from the point of deflection.

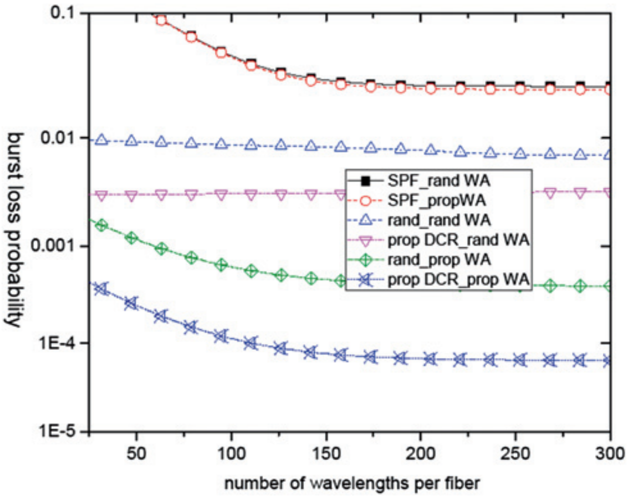


Figure 11: Loss probability as a function of number of wavelengths per fiber.

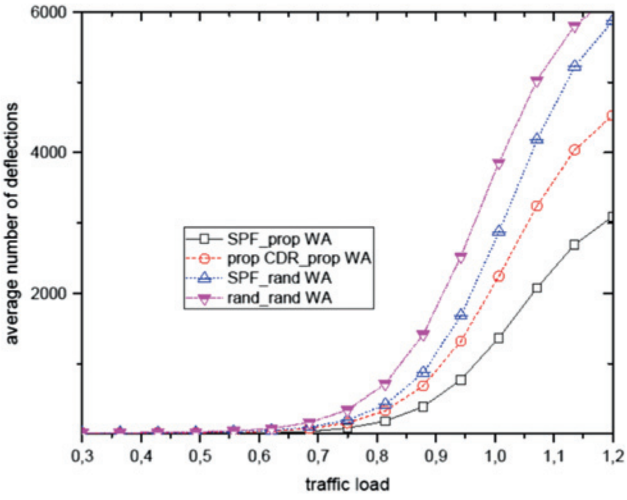


Figure 12: Average number of deflected bursts versus network load.

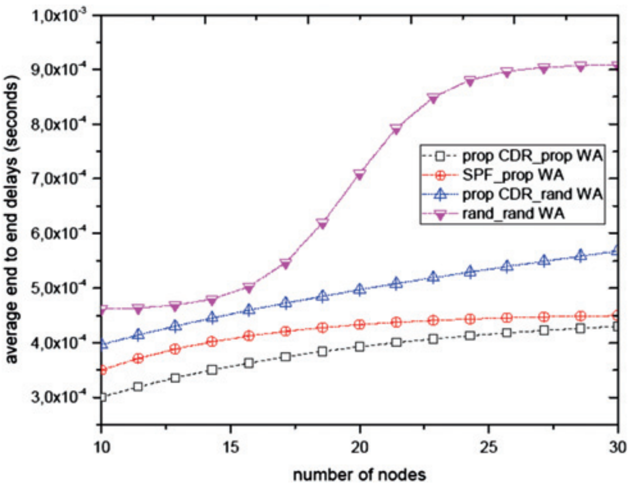


Figure 13: End-to-end delays versus number of nodes.

As seen from Figure 13, both the proposed scheme and SPF_prop WA perform comparatively the same. This is because fundamentally both opt for the shortest paths from the deflection point to the ultimate destination egress node.

7 Conclusion

In this paper, we proposed and described the CDR and wavelength assignment based scheme that allows the deflection of bursts to alternate paths only after controller buffer preset thresholds are surpassed. The scheme couples with a proposed WA approach to significantly improve network performance especially in terms of delay and blocking probability QoS metrics. The proposed scheme's performance is compared to other existing similar schemes or variants such as the ones discussed in [26, 27]. Both analytical as well simulation evaluations were carried out. It is generally found out that the proposed scheme does significantly improve end-to-end blocking as well as minimize end-to-end differential delays caused by bursts originating from the same source having to follow different paths. In that way, jitter levels are minimized, and its effects are negligible.

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