Improving Throughput and Effective Utilization in OBS Networks

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Abstract

This paper considers two important performance measures that have not received much attention in performance studies of optical burst switching (OBS) networks. The first is the so-called *effective utilization* which is the proportion of link capacity used by bursts that eventually reach their destinations. The second considers the throughput of individual source-destination pairs that may indicate unfairness and starving connections. Using these performance measures, we evaluate a new proposed contention resolution strategy called EBSL, which is a combination of the Emulated-OBS wavelength reservation scheme, with the two contention resolution strategies - Burst Segmentation and Least Remaining Hop-count First (L-RHF). The results show that EBSL can prevent congestion collapse of throughput and effective utilization, and reduce the blocking probability under heavy load conditions. We then add deflection routing to EBSL to further increase the throughput under light and medium traffic load. Finally, we replace LRHF by a fairer version of LRHF in EBSL to provide insights into fairness efficiency and tradeoffs. Overall, we demonstrate that OBS can be enhanced to overcome its known traffic congestion related weaknesses of low throughput, ineffective utilization and unfairness.

Keywords: blocking probability, optical burst switching, utilization, effective utilization, segmentation, deflection routing, contention resolution

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1. Introduction

Optical burst switching (OBS) [1, 2] is an optical networking technology for transmitting data from any edge router (ingress node) through optical cross connects (OXC) to another edge router (egress node). OBS is based on assembling packets with the same destination into large data bursts (usually simply called *bursts*) at the ingress nodes. Then these assembled bursts are individually transmitted over the network. This implies that when a burst leaves the ingress node there is no guarantee that it will arrive at the egress node because in OBS, unlike in circuit switching, capacity for a burst is not reserved end-to-end by a multiple-way handshake, and therefore burst contention may occur and bursts may be dumped. OBS is based on one-way reservation, where a burst control packet (BCP) is sent on a separate control channel with some offset time prior to the burst to reserve wavelength channels along the burst transmission path. The offset time provides sufficient time budget for processing the BCP at an electronic switch controller and also for the switch configuration. OBS could also be used in data center networks [3, 4] to avoid end-to-end connection setup delay.

Previous performance studies of OBS networks have focused on blocking probability, e.g. [5, 6], defined as a ratio of the bursts that are lost to the bursts that are sent, and utilization, e.g. [7, 8], defined as the average proportion (over all trunks) of busy channels out of the total number of channels in a trunk. In [9], we have introduced the concepts of effective utilization and ineffective utilization as key performance measures of OBS networks. Effective and ineffective utilizations distinguish between channels used by bursts that eventually reach their destinations, and bursts that are dumped before reaching their destinations, respectively. By reducing the ineffective utilization, the performance and efficiency of OBS network is improved. Ineffective utilization is especially pronounced in periods of heavy traffic. This is equivalent to the well-known effect of congestion collapse in packet switching networks which are characteristics of protocols such as Aloha and TCP. When the network is heavily overloaded, it is 100% utilized, but most of the traffic in it is eventually discarded or dumped due to burst contention. Another important performance measure is the goodput (effective throughput) experienced by individual source destination (SD) pairs. Overall blocking probability may be low and overall effective utilization may be high, but if certain users are starved or suffer low goodput, it may be considered unfair and unacceptable.

The work in [9] shows that under heavy traffic load conditions, the effective utilization and network goodput suffer congestion collapse. Typically under such conditions, the total network utilization is very high, but most of the utilized capacity is used for traffic which is eventually lost and does not reach its destination. Based on the idea to reduce the ineffective utilization by increasing the likelihood that bursts which have already used a significant amount of network resources reach their destinations, thereby increasing network throughput, we proposed a new contention resolution strategy - EBSL in [10], which is a combination of Emulated-OBS [11] wavelength reservation methods and two burst contention resolution strategies: Burst Segmentation [12] and the Least Remaining Hop-count First scheme (LRHF) [13]. EBSL can reduce the ineffective utilization, thereby improving the performance and efficiency of OBS network. Since the adverse effect of ineffective utilization is most pronounced during period of heavy traffic load, EBSL is especially beneficial under heavy load conditions. Heavy load periods are not uncommon [14] and any Internet protocol should maintain efficiency during such periods. In EBSL, bursts with fewer remaining hops have higher priority so they preempt overlapped segments of other lower priority bursts, and these preempted segments are dumped. Accordingly, we consider the packet blocking probability instead of burst blocking probability as a more appropriate performance measure. OBS is a method for transmission of large data bursts without the need to connection or lightpath setup. It can be used end-to-end and not only between edge routers (with packet aggregation, etc.). When a lightpath is set up for a dynamic connection, a data burst may be ready to go (e.g. Large Hydron Collider or inter-data-center applications). In such cases, the burst has already been assembled, so assembling bursts may be independent of OBS. Accordingly, we ignore burst assembly process and only consider the end-to-end blocking probability.

In this paper, we provide new results of EBSL and compare it with other strategies. Furthermore, to improve the fairness of EBSL, we consider a modification of EBSL which we call *Fair EBSL* (F-EBSL). In F-EBSL we limit preemption of lower priority bursts (according to the least remaining hops) to only bursts that originally required a number of hops between SD pairs smaller than the preempting burst. This fairer approach aims to protect bursts that require long routes. Comparing F-EBSL and EBSL for a wide range of parameters gives us an appreciation of the possibilities to trade off fairness and efficiency in OBS networks. We also study the performance of the combination of EBSL and deflection routing (EBSL-D) in OBS networks and demonstrate for the cases studied that EBSL-D outperforms EBSL under light and medium traffic load and its performance is not worse than that of EBSL under heavy traffic load.

This paper is written from a teletraffic perspective ignoring all physical layer issues [15].

1.1. Related Work

In the original OBS (O-OBS) [1], the offset time of a burst is set up at the edge node according to its path length. At each core node, the offset time decreases by the time the BCP spends in the switch controller.

To reduce the control complexity, the Emulated-OBS (E-OBS) architecture has been proposed in [16, 11] to avoid the so-called phantom bursts in OBS, where a BCP continues its travel towards the destination and makes reservations for a preempted and dumped burst. In E-OBS, an edge node sends the BCP and the burst together, and then at each core node the burst is postponed an offset time by the additional fiber delay units inserted in the data path at each core node. After the offset time expired, the data bursts and the BCP are either send together to the next node or drop together.

Since OBS uses one-way reservation, there is no guarantee that a transmitted burst will reach its destination, and bursts may be dropped at intermediate nodes due to contention, therefore burst loss because of contention is a major concern in OBS networks [7]. In the following we provide background on three contention resolution strategies used in this paper, namely, Burst Segmentation, LRHF and deflection routing.

The authors of [13] proposed preemptive priority burst-service policies in each switching node, whereby the priority depends on the route a burst follows, referred to as Least Remaining Hop-count First (LRHF). With LRHF, in every wavelength channel, each transmitted burst can be preempted by any newly arrived burst that has a strictly fewer remaining number of hops to its destination. In this paper, we consider a modified version of LRHF where instead of preempting entire bursts, we combine the priority algorithm with segmentation. This has the additional benefit that our strategy is totally distributed where a central controller is not required. The work in [17] includes an evaluation of blocking probability of LRHF using a Markov chain simulation which did not consider the effect the offset time and E-OBS.

Burst segmentation [12, 18, 19] is another method that aims to solve the burst contention problem. During contention, burst segmentation enables dumping only the parts (segments) of a contending burst which overlap with other bursts, instead of dumping the entire burst. There are two approaches to perform segmentation: one is to dump segments belonging to the tail of the earlier burst (tail segmentation) [12] and the other approach is to dump segments of the head of the contending burst (head segmentation) [20]. We use tail segmentation in this paper.

Deflection routing [21, 22] is another key contention resolution option. If a burst arrives at a switch and finds its output trunk is already occupied, then it will be deflected to other trunks connected to that switch. The performance analysis of deflection routing has attracted significant attention [23, 24, 25, 26, 22]. Deflection routing performs well under light and medium traffic load but suffers instability under heavy load [27, 28, 29]. There are several approaches to overcome this instability problem. Limited fiber delay lines or access control of the local traffic was suggested in [27] to keep the network stable. The authors of [28] proposed to deflect a burst with a probability p instead of deflecting always. When the traffic is heavy, the value of p is set to zero so that deflection routing is disabled. Another approach is to reserve some of the capacity on each trunk for bursts that have not been deflected [29]. However, numerical results in [30] shows that under heavy load, deflection routing (with wavelength reservation) may have higher burst blocking probability than OBS without deflection routing. This is because under heavy load, deflection increases the network traffic load that leads to congestion. Another solution is shortest path prioritized random deflection routing [31] which gives higher priority to the bursts that were deflected fewer times and let higher priority bursts preempt lower priority bursts in case of contention, when an arriving burst finds the output trunk fully occupied. The numerical results in [32] show that the shortest path prioritized random deflection routing works well under light and medium traffic but under heavy load, its performance is almost the same as when deflection routing is excluded.

1.2. Contribution of This Paper

The challenges in the deployment of OBS have been related to (1) physical layer issues, and (2) low effective utilization associated with collision and congestion collapse. Although we do not address the physical layer issues, this paper makes significant progress towards solving the low effective utilization problem.

The contribution of this paper is fourfold.

1. In this paper, we combine several previously proposed contention resolution strategies for OBS networks and we study the performance of the combine strategy - EBSL. Although the particular techniques that we combine have already been introduced in the literature, the particular way the strategies here are combined produces schemes that overcome the known weaknesses associated with congestion collapse and this was not done before. In addition, the performance analysis focuses on goodput and effective utilization in this paper, which have not been considered in most OBS papers. In addition to the consideration of effective utilization, we use Ideal OC-S (I-OCS) [9] as a benchmark for OBS performance in this paper. Using

I-OCS as benchmark provides a methodology for OBS performance evaluation, which have rarely been used in OBS performance studies literature. I-OCS represents an ideal transport and a target to aim for in the design of OBS networks. In I-OCS, we ignore the lightpath setup time and the effect of the waste of utilization associated with a resource is being reserved until the first payload actually arrives. This wastage of OCS can be significant especially for circuits with short holding times, e.g., less than one round trip time. We also assume that I-OCS channels during holding time are fully utilized. We consider I-OCS with alternate routing as a benchmark of EBSL-D under light and medium traffic load conditions. We use discrete event simulation that enables us to include the effect of the offset time and use E-OBS architecture instead of original OBS to eliminate the phantom bursts. Note also that unlike [13] which preempts entire bursts, among the alternatives we examine, we consider an enhancement of LRHF priority concept to include tail segmentation so that the EBSL strategy is totally distributed.

2. The paper uses the lessons of this comparison to consider and thoroughly study the performance of an OBS design, namely EBSL, that integrates various existing proposals and achieves high resilience in terms of goodput even under heavy traffic conditions.

3. It introduces the fairer version of EBSL (denated F-EBSL) and evaluates its performance considering fairness efficiency tradeoffs.

4. It considers a combination of EBSL and deflection routing (donated EBSL-D) and study its performance tradeoffs.

Note that EBSL was originally introduced in the conference version of this paper [10]. However, there we only briefly introduced the concept of EBSL, with limited performance study (only considering a ring network topology).

1.3. Organization of This Paper

The remainder of the paper is organized as follows. The network model is introduced in Section 2. In Section 3, the algorithms for the EBSL, F-EBSL and EBSL-D are introduced. The equations for calculating the packet blocking probabilities, utilization, goodput and effective utilization are discussed in Section 4. Numerical results are shown in Section 5. Finally, the paper is concluded in section 6.

2. Network Models

As discussed, we consider an OBS network model and its equivalent I-OCS benchmark. The main difference between the two is that in OBS, a burst is transmitted hop-by-hop until it reaches its destination successfully or until it is blocked and dumped. By contrast, in I-OCS, data cannot access the network unless the availability of an end-to-end lightpath can be guaranteed. Both models are characterized by a network that comprises a set of nodes $\alpha = \{1, \ldots, N\}$ connected by a set of trunks $\mathcal{J}$. Every trunk $j \in \mathcal{J}$ comprises f_j fibers, each of which supports w_j wavelengths, so a trunk carries $C_j = f_j w_j$ wavelength channels. The length of each trunk in the network is known.

Let β be a set of directional SD pairs. Every SD pair $m = \{s, d\} \in \beta$, is defined by its end-nodes. Here the source s represents an ingress node and destination d represents an egress node. In this paper, we neglect the burst assembly process and assume that bursts of SD pair $m = \{s, d\}$ are generated at source s according to a Poisson process with parameter λ_m and the bursts are fully filled with packets. Note that some of the burst assembly schemes [33, 34] may send bursts that are only partially filled with packets or even send empty bursts to the network, and these bursts will cause ineffective utilization in the network. We neglect these inefficiencies related to burst assembly in this paper.

In OBS networks, if more than a single route between the source and the destination are available for a directional SD pair $m \in \beta$, we choose the route with the smallest number of hops as the primary path of this SD pair.

Consider the set

$$\{\mathbf{U}_m(0), \mathbf{U}_{m,j_1}(1), \mathbf{U}_{m,j_2}(1), \ldots, \mathbf{U}_{m,j_n}(T_m)\}$$

as the primary and alternative routes of the directional SD pair $m \in \beta$. In this set, $\mathbf{U}_m(0)$ is the primary path, and $\mathbf{U}_{m,j}(d)$ represents the alternative path deflected from trunk j, that has already been deflected d times (including this deflection). The variable $T_m(OBS)$ denotes the maximal number of deflections of the directional SD pair m in OBS networks. Note that the value of $T_m(OBS)$ is a function of the network topology which limits the number of deflections. For example, $T_m(OBS) = 0$ in the trivial example of a two-node network where two opposite-directional trunks connect the two nodes.

Any burst is permitted to be deflected at most $D(OBS)$ times. A burst is blocked, dumped and cleared from the network, if it arrives at a given node where all output wavelengths at the desired direction are busy and the burst reaches the limit $D(OBS)$ of allowable number of deflections, or all output wavelengths at the desired direction are busy, and all the wavelengths in trunks belonging to alternative paths are also busy. Setting the limit $D(OBS)$ as an upper bound on the number of deflections implies that the maximum number $R_m(OBS)$ of deflections on a burst of a directional SD pair m where

$$R_m(OBS) = \min\{T_m(OBS), D(OBS)\}.$$

In I-OCS networks, for a directional SD pair $m \in \beta$, it is likely that there are multiple routes that do not share a common trunk. Such routes are often called *edge-disjoint paths* or *disjoint paths*[35, 36, 37]. Edge-disjoint alternate routing is often used to achieve load balancing in optical and other networks [38, 39].

For each $m \in \beta$, we choose a least-hop route as the primary path $U(m,0)$ for the directional SD pair m. If there are multiple least-hop routes, we randomly select one of them as the primary path. Then considering a new topology where the trunks of the primary path are excluded, the least-hop route in the new topology is chosen as the first alternative path for this SD pair. Again ties are randomly broken. Therefore, all the paths for the SD pair m, including the primary path and several alternative paths, are edge-disjoint. The variable $T_m(OCS)$ is the maximal number of available alternative paths a directional SD pair m can have based on the network topology in I-OCS.

Furthermore, a maximum allowable number $D(OCS)$ of overflows is set for calls for each directional SD pairs in β. Setting the limit $D(OCS)$ as an upper bound on the number of overflows implies that a call of the directional SD pair m, can only overflow $R_m(OCS)$ times in I-OCS networks where

$$R_m(OCS) = \min\{T_m(OCS), D(OCS)\}.$$

When a call arrives and there are free channels on all trunks along its primary path, the call will be transmitted on its primary path. Otherwise, it will be overflowed to its first alternative path. The procedure then repeats itself. The call is blocked, dumped and cleared from the network if all $R_m(OCS)$ paths are attempted.

We set the 1-hop offset time in the OBS networks to 10 μs, and the burst/call duration times are assumed to follow an exponential distribution with a mean of 0.25 ms (2.5 Mb data burst at 10 Gb/s). Each packet size is 1250 Bytes/packet, so on average there are 250 packets in a burst. The switching time between the burst control packet (BCP) and data burst is below μs in fast switching [40, 41], which is quite small compared to the burst duration, so we ignore the switching time. We also ignore the lightpath set up time in I-OCS networks.

Results presented in this paper are equally applicable to networks with no wavelength conversion which has f_j, instead of $f_j w_j$, channels per trunk where the arrival rate for the SD pair m is λ_m / w_j.

A selected set of notations defined in this section are presented in Table 1.

Table 1: Table of selected notations

Notation	Definition
α	A set of nodes
$\mathcal{J}$	A set of trunks
β	A set of SD pairs
λ_m	Burst arrival rate of the SD pair m
C_j	Number of wavelength channels on trunk j
$T_m(OBS)$	The maximal number of deflections of the directional SD pair m in OBS networks
$T_m(OCS)$	The maximal number of available alternative paths of the directional SD pair m in I-OCS networks
$D(OBS)$	The maximum allowable number of deflections in OBS networks
$D(OCS)$	The maximum allowable number of overflows in I-OCS networks
$R_m(OBS)$	The maximum number of deflection on a burst of the directional SD pair m in OBS networks
$R_m(OCS)$	The maximum number of overflow on a burst of the directional SD pair m in I-OCS networks

3. EBSL, F-EBSL and EBSL-D

According to EBSL, each burst is given a different priority based on the number of remaining hops, and the bursts with fewer remaining hops will have higher priority. When a burst travels along its path, its priority is increased by one every hop. Thus, a burst transmitted on its last hop or a burst that attempts to find a channel on its last hop have the highest priority–priority 1. Then a newly arriving burst with n-hop path has priority n and when it finishes its transmission on the first trunk, its priority increases to $n-1$. On average, bursts that have used up a significant network resources have lower probability to be preempted and higher probability to preempt other bursts and therefore higher probability to reach their destinations.

When a burst arrives at a trunk, it will first try to find a free channel for its transmission. If there is no free channel on that trunk, burst contention occurs. Fig. 1 illustrates the two contention scenarios. If the contending burst finds all the transmitted bursts on the trunk has higher or equal priority, the entire burst is dumped from the network as shown in Fig. 1 (b). If the contending burst finds one or more transmitting bursts on the trunk with a lower priority, it will select the transmitting burst with lowest priority (or randomly select one among the bursts with lowest priority) and preempt the overlapped segments of that lowest priority burst as shown in Fig. 1 (a). The preempted segments will be dumped from the network. When such burst segmentation occurs, a reservation cancel packet (RCP) is formed immediately and is transmitted on the control channel to the downstream hops on the path of the segmented burst to release the resource reserved for the dumped segments. Since burst segmentation occurs without consideration of the IP packets positions within a burst, it almost always creates an incomplete packet at the end of the segmented burst. When a segmented burst reaches its destination, if its last packet is received incompletely, then this incomplete packet will be dumped.

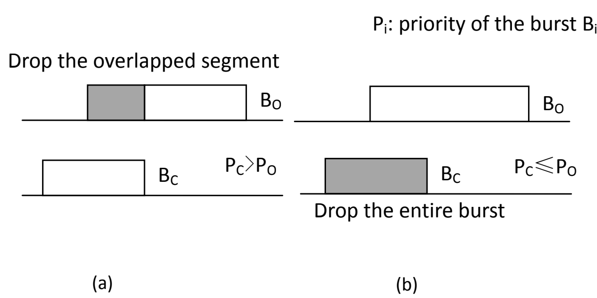

Figure 1: Selective dropping for two contending bursts in EBSL

To protect bursts that require long routes, we introduce the fairer version of EBSL, namely, F-EBSL. According to F-EBSL, when a burst arrives at a trunk where it cannot find a free channel for its transmission, it can preempt a lower priority burst which is being transmitted on that trunk, only if this lower priority burst originally required a path with an equal or lower number of hops than itself.

If all the transmitted bursts have higher or equal priority, or they require larger total number of hops on their paths, the arriving burst will be dumped. Otherwise, the arriving burst will select the lowest priority burst (or randomly select one if there are more than one bursts have the same lowest priority) amongst the bursts with lower priority that originally required an equal or lower number of hops and preempt the overlapped segment of that burst (as shown in Fig. 2).

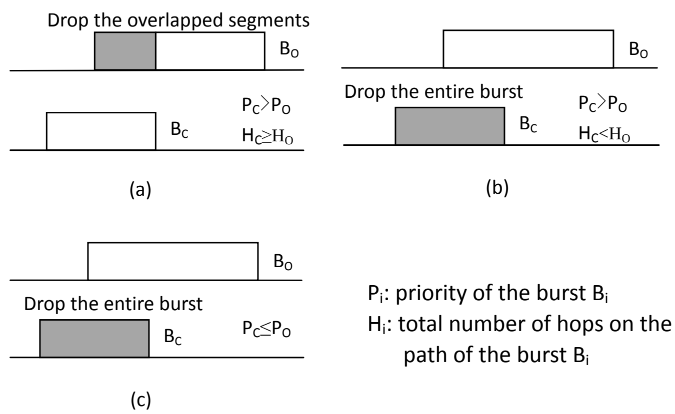

Figure 2: Selective dropping for two contending bursts in F-EBSL

Under EBSL-D, segmentation always happens before deflection and once a burst or a segmented part of a burst is deflected, its priority will be set to $L+1$, where L is the total number of trunks in the network, and its priority will not increase when it completes each one hop transmission. This guarantees that the deflected bursts always have the same lowest priority in the network, so they can be segmented or preempted by bursts traveling on their primary paths but they themselves can never preempt other bursts.

In EBSL-D OBS networks, when a burst arrives at a trunk j on its primary path, it will first try to find a free channel for its transmission. If there is no free channel on trunk j, burst contention occurs. If the burst finds that all the transmitted bursts on trunk j have higher or equal priority, the entire burst is deflected to the first overflow trunk j_1 of trunk j and the priority of the burst is set to priority $L+1$. If the first overflow trunk j_1 is also fully occupied, then the burst is deflected again to the second overflow trunk j_2 of trunk j. The deflection procedure repeats itself until the burst finds a free channel on the overflow trunks. If no overflow trunk is available, or the maximum allowable number of deflections is reached, the burst is dumped. If the burst finds one or more transmitting bursts on the trunk that has a lower priority, it will select the transmitting burst with lowest priority (or randomly select one among the bursts with the same lowest priority) and preempt the overlapped segments of the burst. The preempted segments are deflected to its overflow trunk or blocked if there is no such a trunk.

The deflected bursts have the lowest priority in the network and primary bursts always have higher priority than deflected bursts. Therefore, the deflected bursts will not affect the access of the primary bursts. This guarantees that there is no instability problem under heavy traffic load.

4. Performance Evaluation

We use discrete event simulation to study the performance of our EBSL, F-EBSL and EBSL-D strategies. Let $packetB_m$ and $packetS_m$ be the number of blocked packets and the number of packets that reach their destinations for SD pair m, respectively. We ignore the out-of-order problem of deflection routing and only count the number of packets when we calculate the packet blocking probabilities and network goodput. The packet blocking probability for each SD pair is then defined as

$$BP_m = \frac{packetB_m}{packetB_m + packetS_m}, \tag{1}$$

and the packet blocking probability of the network is evaluated as

$$BP = \frac{\sum_{m \in \beta} packetB_m}{\sum_{m \in \beta} packetB_m + \sum_{m \in \beta} packetS_m}. \tag{2}$$

For every SD pair $m \in \beta$, let $g(m)$ be the goodput for SD pair m given by

$$g(m) = \frac{\lambda_m}{\mu_m} \times (1 - BP_m), \tag{3}$$

where μ_m is the mean burst service rate for SD pair m.

The network goodput g_n is the total goodput of all SD pairs and is given by

$$g_n = \sum_{m \in \beta} g(m). \tag{4}$$

The utilization U_j of trunk j is

$$U(j) = \frac{1}{C_j} \sum_{i=0}^{C_j} i \times q_j(i), \tag{5}$$

where $q_j(i)$ is the probability that there are i busy channels on trunk j. The effective utilization EU_j of trunk j is

$$EU(j) = \frac{1}{C_j} \sum_{k=0}^{C_j} k \times p_j(k). \tag{6}$$

where $p_j(k)$ is the probability that there are k busy channels occupied by packets that successfully reach their destinations on trunk j. Then, network utilization U_n and effective utilization EU_n are the averages of trunk utilization and trunk effective utilization, over all trunks, respectively. They are obtained by,

$$U_n = \frac{1}{L} \sum_{j \in \mathcal{E}} U(j), \tag{7}$$

and

$$EU_n = \frac{1}{L} \sum_{j \in \mathcal{E}} EU(j). \tag{8}$$

The network ineffective utilization is defined as the network utilization used by packets that are dumped before they reach their destinations. It is obtained by

$$IU_n = U_n - EU_n. \tag{9}$$

5. Numerical Results

In this section, simulation results were generated for a 6-node ring network and the 14-node 21-link NSFNet. We use them to illustrate that EBSL, F-EBSL and EBSL-D strategies can significantly improve the goodput and effective utilization in OBS networks. The topology of the 6-node ring network is shown in Fig. 3, where the arrows represent unidirectional trunks with length 1000 km. The topology of the 14-node NSFNet is shown in Fig. 4, where each line between two nodes represents two opposite unidirectional trunks. The length of each trunk in Fig. 4 is given in units of km. The simulation results are mainly under heavy traffic conditions where the original OBS is most vulnerable to congestion collapse.

Even if networks are over dimensioned, there are periods of times with heavy traffic and congestion, and investigations on heavy traffic conditions are therefore always important. Error bars for 95% confidence intervals based on Student's t-distribution are provided for all the simulation results although in many cases the intervals are too small to be clearly visible. Just Enough Time (JET) scheduling [17] is used for all strategies.

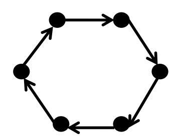

Figure 3: 6-node ring network topology.

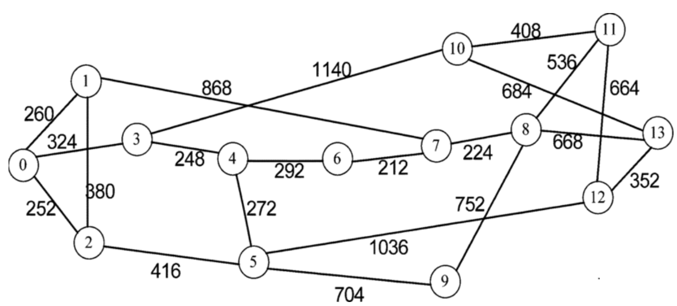

Figure 4: 14-node 21-link network topology.

5.1. Performance of EBSL and F-EBSL in a 6-node ring network

We first consider the 6-node ring network with all possible six 3-hop SD pairs in clockwise direction and having different source nodes. Here the *n*-hop means that a burst from that SD pair has *n* trunks along its path between the source node and destination node. Each trunk in the ring network has 50 channels and the burst arrival rates to all SD pairs are identical. As there is only one path between any SD pair, deflection routing is not enabled in this case. The results are shown in Fig. 5. JET resource reservation scheme is used in O-OBS.

Firstly, comparing the performance of O-OBS and E-OBS, we observe that E-OBS outperforms O-OBS as shown in Fig. 5, which is consistent with [16]. This is because in O-OBS, the blocking probability of a transmitting burst increases when it is closer to its destination, and on the contrary, in E-OBS, the blocking probability of a burst keeps the same on the trunks along its path. For detailed explanations, please see [11].

Comparing O-OBS and EBSL, we observe in (b) and (d), a reduction of the effective utilization and goodput collapse in the O-OBS networks; this is consistent with [9]. However, when we apply EBSL in the OBS network, the effective utilization is significantly improved as shown in Fig. 5 (d). This is because giving priority to bursts with fewer remaining hops enables them to preempt the overlapping segments of other bursts with lowest priority and to complete their transport successfully. In this way, the resources they have used contributes to effective utilization. When we set the same capacity for each trunk, the same arrival rate for each SD pair, the same length for each trunk, and consider only 3-hop SD pairs, then the traffic is the same on each trunk and for each SD pair and all the new arrival bursts have the same priority (priority level 3, lowest priority). Thus a new arrival burst can either find a free channel to transmit or be dumped, and cannot preempt any other bursts transmitted in the network, so that bursts have the highest blocking probability at their first hop. When the burst completes its journey on its first hop, its priority level decreases and therefore its priority increases, then on its second hop, the burst has a higher probability to find a channel (either a free channel or a busy channel occupied by a lower priority burst) and lower probability to be segmented and preempted by other higher priority bursts. Thus for a new burst it is more difficult to access the network, but as long as it accesses the network, it has a higher probability to reach its destination. This increases the effective utilization and reduces the ineffective utilization.

Then as more resources are used effectively, the goodput of the network also increases significantly as shown in Fig. 5 (c). With the same offered load, if the goodput is increased, more bursts are successfully transmitted, so that with EBSL, the blocking probability is reduced as shown in (a). Comparing to the I-OCS benchmark shown in Fig. 5, we observe that the network blocking probability, goodput and effective utilization of E-OBS with EBSL are almost the same to those of its I-OCS benchmark under the same traffic load.

Fig. 5 display the results for E-OBS with only segmentation (tail dropping) but no LRHF, donated as E-OBS-S. We observe that segmentation can improve the goodput and effective utilization of the network, but it cannot totally eliminate the goodput collapse.

Since the network and traffic matrix are all symmetric, and since there are only 3-hop SD pairs in the network, all SD pairs are treated fairly and there are no unfairness issues to discuss here. To illustrate unfairness and to examine the performance of F-EBSL, we next consider 2 types of bursts: one type is called

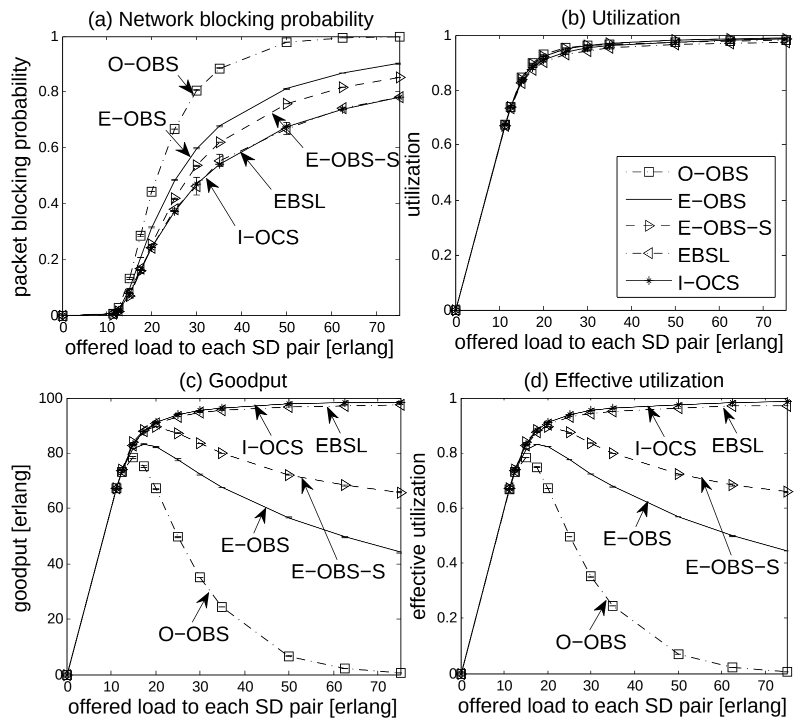

Figure 5: The blocking probability, utilization, goodput and effective utilization in a 6-node ring network with only 3-hop path SD pairs for the I-OCS, O-OBS, E-OBS, E-OBS with tail segmentation (E-OBS-S) and EBSL.

the 2-hop bursts requiring a 2-hop path and the other with 3-hop bursts requiring 3-hop paths. All possible six 2-hop SD pairs and all possible six 3-hop SD pairs in clockwise direction have an offered load larger than zero.

In Fig. 6, we provide goodput results obtained by applying EBSL in such a network. Each trunk in this ring network has 50 channels and the burst arrival rates to all SD pairs are identical. We observe that the average goodput of all the 2-hop bursts increases, but the average goodput of all the 3-hop bursts decreases when we apply the EBSL strategy. This is because in EBSL, a newly arriving 2-hop burst has preemptive priority over a newly arriving 3-hop burst, and the 2-hop burst maintains its priority over the 3-hop burst if both successfully complete the same number of hops. Accordingly, EBSL discriminates against traffic that requires more hops in favour of traffic that requires fewer hops.

Next we consider the fairer version of the EBSL strategy, namely F-EBSL, where we never allow a burst to preempt the overlapped segments of a burst that

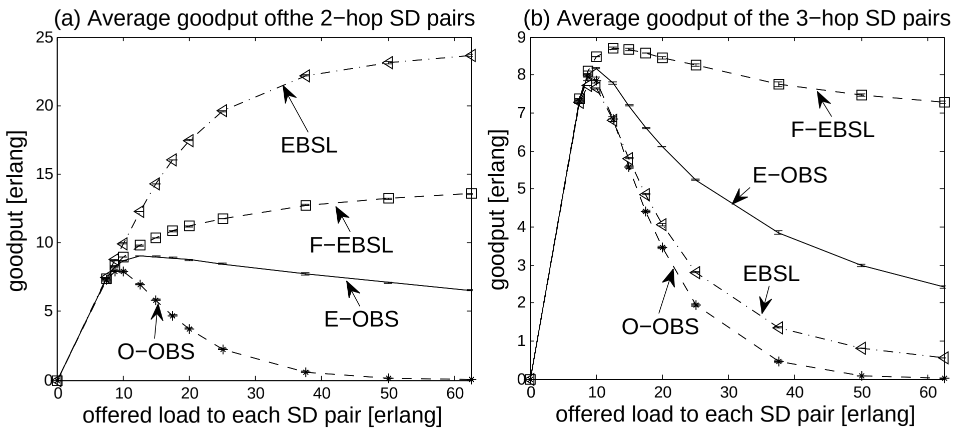

Figure 6: (a) Average goodput of the 2-hop SD pairs and (b) Average goodput of the 3-hop SD pairs in a 6-node ring network for O-OBS, E-OBS, EBSL and F-EBSL.

originally required more hops than the preempting burst. In the case of our 6-node ring network model, 2-hop bursts can never preempt the overlapped segments of a 3-hop burst, but 2-hop bursts (on their second hop) with higher priority can still preempt the overlapped segments of 2-hop bursts (on their first hop) with lower priority. The goodput results of F-EBSL are shown in Fig. 6. We observe that the average goodput of both 3-hop SD pairs and 2-hop SD pairs increases relative to O-OBS, but the total goodput of F-EBSL is lower than that of EBSL as shown in Fig. 7 (c). However, under F-EBSL, more 3-hop bursts successfully reach their destinations and they use more network resources than the 2-hop bursts. Therefore the effective utilization of F-EBSL is higher than that of EBSL as shown in Fig. 7 (d). The results of I-OCS (as a benchmark) are also shown in Fig. 7. In Fig. 7 (c) and (d), we observe that I-OCS has larger effective utilization than EBSL and F-EBSL under the same traffic load, but its goodput is lower than that of EBSL. At first this may seem counter intuitive, but a simple example shown in Fig. 8 explains the reason. Fig. 8 describes a case where there are 4 nodes, 3 trunks and each trunk has 2 channels. Cases (a), (b) and (c) show the bursts transmitted on each channel at three different times. In the three cases, bursts AC (send from A to C), bursts AD, bursts CD and burst BD all successfully reach their destinations, so in (a) and (b), the effective utilization is 100% and in (c), the effective utilization is 66.7%. If burst AC, burst AD, burst CD and burst BD have the same traffic load, then comparing (a) and (b), we observe that although the effective utilization is

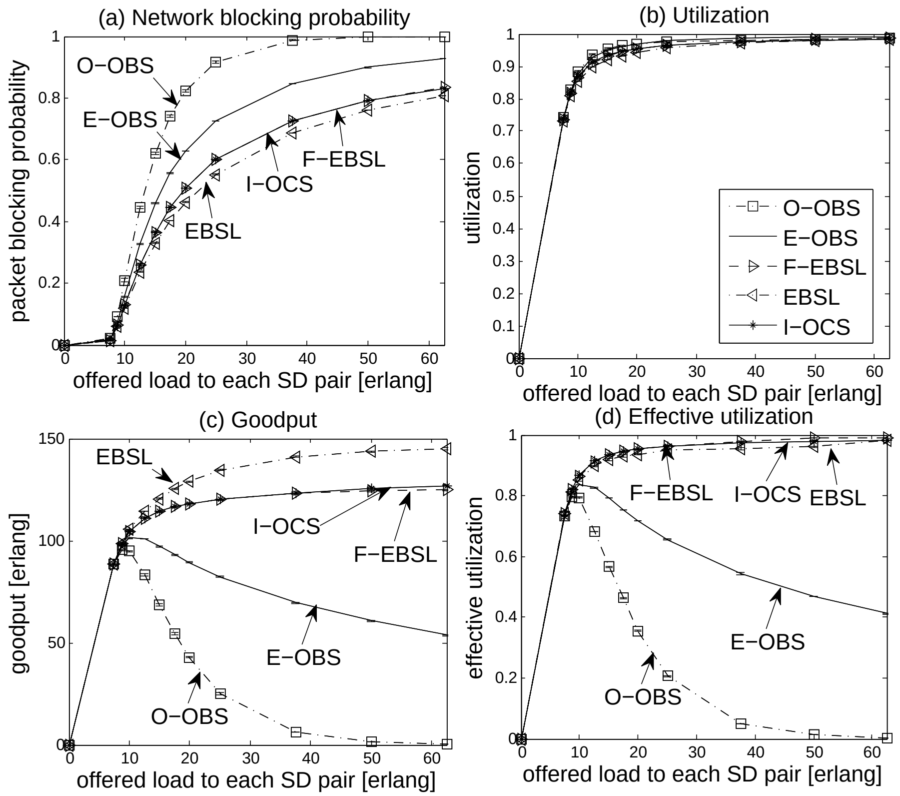

Figure 7: The blocking probability, utilization, goodput, and effective utilization in a 6-node ring network with all 2-hop and 3-hop SD pairs for O-OBS, E-OBS, EBSL, F-EBSL and I-OCS.

the same in the two cases, the goodput of (a) is higher than (b), because in (a), burst AC needs to travel 2 hops, burst CD needs 1 hop but burst AD needs 3 hops, then 2 burst AC and 2 burst CD together use the same network resources as 2 burst AD; and comparing (b) and (c), we observe that the goodput is the same in the two cases but the effective utilization in (b) is higher than that in (c). This example illustrates how EBSL that favours short flows can accommodate more bursts in the network and hence increases the goodput.

5.2. Performance of EBSL, F-EBSL and EBSL-D in the NSFNet

The results for the NSFNet are shown in Fig. 9. We choose all the possible SD pairs, and for each SD pair the path with least number of hops is selected. Each trunk in the network has 50 channels and the burst arrival rate to each SD pair

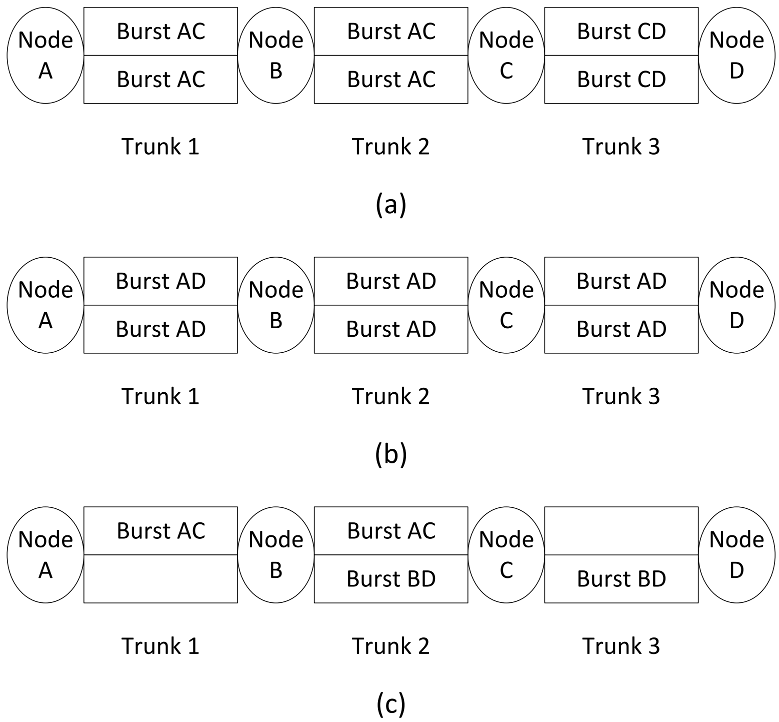

Figure 8: An example of goodput and effective utilization in OBS network.

is the same. In E-OBS with deflection routing strategy, the maximum number of deflections allowed is 3.

Firstly, in Fig. 9, we observe that for EBSL, the trends and behaviors of the results presented for NSFNet are consistent with the results obtained for the 6-node ring network - both the goodput and effective utilization are improved using EBSL relative to O-OBS as shown in Fig. 9 (c) and (d) and the blocking probability is reduced as shown in (a).

One reason that in EBSL, effective utilization and goodput are improved is the same as that in the 6-node ring network - bursts that have already used network resources have higher priority and are more likely to reach their destinations. Another reason is that the discrimination against bursts that require paths with more hops reduces the possibilities of such bursts consuming much resources and then being dumped, and vice versa. In addition, favouring short flows can accommodate more bursts in the network and hence increases the goodput. Bursts that require a small number of hops have higher priority which enables them to access and complete their journey successfully. This is especially applicable in the

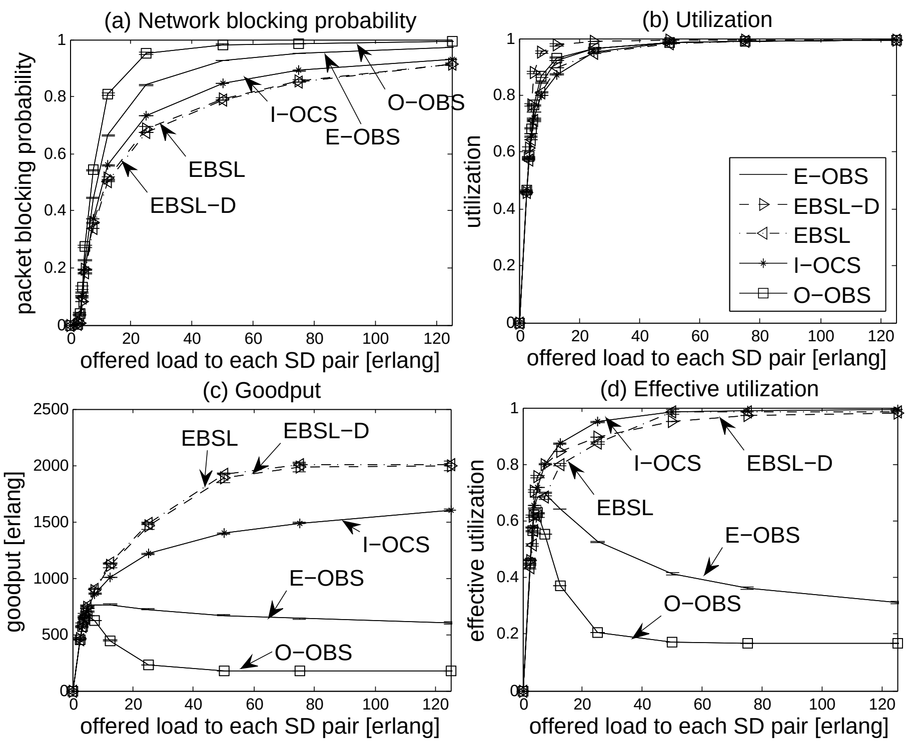

Figure 9: The blocking probability, utilization, goodput and effective utilization in the NSFNet for the networks with O-OBS, E-OBS, EBSL and EBSL-D.

NSFNet example where path lengths have larger variability than in the 6-node network.

The results of the combination of EBSL and deflection routing (EBSL-D) are also shown in Fig. 9 and Fig. 10. In Fig. 9, I-OCS without alternative routing is used as a benchmark, and in Fig. 10, I-OCS with alternative routing is used as the benchmark and the value of $D(OCS)$ is set to 3. We also set the value of $D(OBS)$ to 3. From these figures, we observe that EBSL-D significantly reduces the network blocking probability, and its performance is better than EBSL under light and medium traffic load as shown in Fig. 10. This is explained by a known effect of deflection routing [30]. Under light and medium traffic load, the network is not fully utilized (as shown in Fig. 10 (b)), EBSL-D allows to deflect the contending bursts or the overlapped segments increases the network utilization, so that more packets can reach their destinations which leads to the increase of the goodput and the reduction of the network packet blocking probability comparing to EBSL.

The performance of EBSL-D is close to that of EBSL under heavy traffic load as shown in Fig. 9 because when the network utilization is close to 100%, it is difficult for the deflected bursts to find free channels on their overflow trunks, so that deflection helps little in this situation, and even if the deflected bursts can find free channels, they are likely to be preempted by higher priority primary path bursts. Comparing the performance of EBSL-D and EBSL, we observe no instability problem in EBSL-D under heavy load conditions since the condition that the network is fully filled with deflected bursts which prevents the primary bursts to access the network will not happen in EBSL-D.

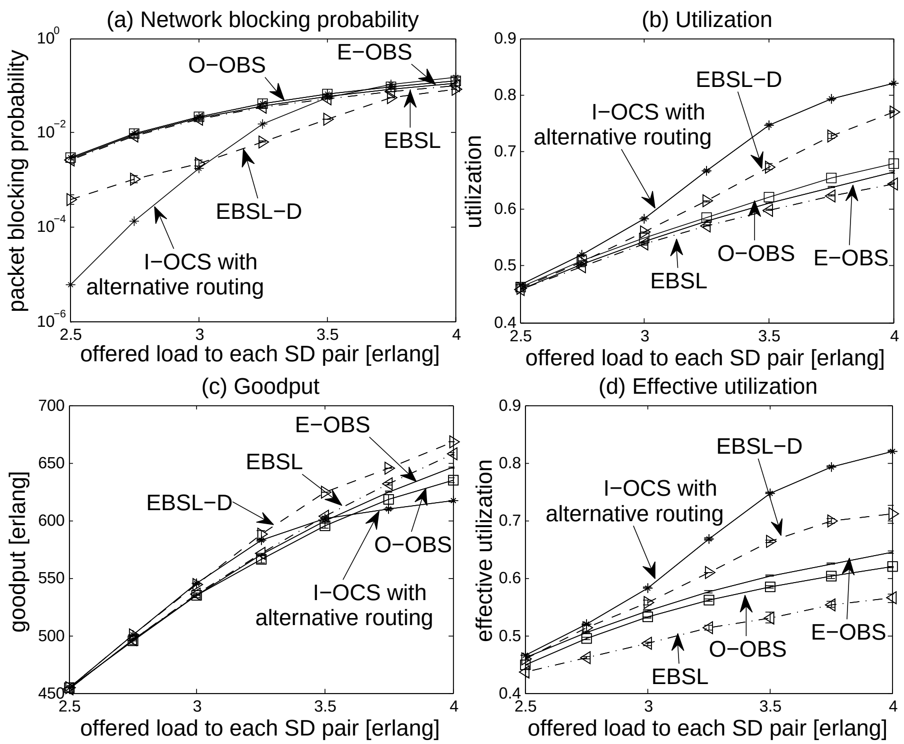

Figure 10: The blocking probability, utilization, goodput and effective utilization in the NSFNet for the networks with O-OBS, E-OBS, EBSL, EBSL-D and I-OCS with alternative routing under light and medium traffic load.

In the case presented in Fig. 10, the utilization and effective utilization for the EBSL-D strategy are lower than those for I-OCS with the alternative routing strategy under light, medium and high traffic load. In addition, the goodput for the EBSL-D strategy are higher than that for I-OCS with the alternative routing strategy under medium and high traffic load. This is because in EBSL-D, the bursts with fewer initial hops, which use fewer network resources, have a higher probability to successfully reach their destinations than that they do in I-OCS with the alternative routing strategy.

The performance comparison of EBSL and F-EBSL in NSFNet is illustrated in Fig. 11 and 12. There are only three kinds of bursts in the NSFNet: 1-hop bursts, 2-hop bursts and 3-hop bursts. From Fig. 11, we observe that EBSL discriminates in favor of bursts that require fewer hops and in contrast, O-OBS is not in favor of bursts that require fewer hops. Since a burst that require fewer hops uses less network resources, the network can serve more such bursts than those requiring more hops. Thus, as shown in Fig. 12 (c), with EBSL, the network goodput is higher than that under O-OBS for the same offered load. As E-OBS is relatively fair to all the bursts, the average goodput under E-OBS for bursts with various hop numbers are between those under EBSL and O-OBS in most of the range of the offered load shown in Fig. 11.

In F-EBSL, comparing to EBSL, the goodput of the 1-hop bursts is partly sacrificed to provide higher probability for the bursts requiring 2 and 3 hops, thus the average goodput of the 1-hop bursts in F-EBSL is lower than that in EBSL but the average goodput of the 2-hop bursts and the average goodput of the 3-hop bursts in F-EBSL are higher than those in EBSL for most of the range of offered loads shown in Fig. 11. The network goodput in F-EBSL is lower than that under EBSL but higher than those in E-OBS and O-OBS under the same offered load as illustrated in Fig. 12 (c). Since there is no ineffective utilization in I-OCS, the averaged goodput for all bursts are higher than that in E-OBS.

6. Conclusion

In this paper, we have introduced the EBSL strategy in OBS networks that can significantly reduce the ineffective utilization, eliminate the collapse of goodput and effective utilization, and improve QoS. We have also considered fairness issue and introduced the F-EBSL strategy which partly sacrifices performance to provide higher probability for the bursts that require more hops to successfully reach their destinations. We have also demonstrated that the combination of EBSL with deflection routing has achieved a better performance than EBSL under light and medium traffic load and a similar performance to EBSL under heavy traffic load.

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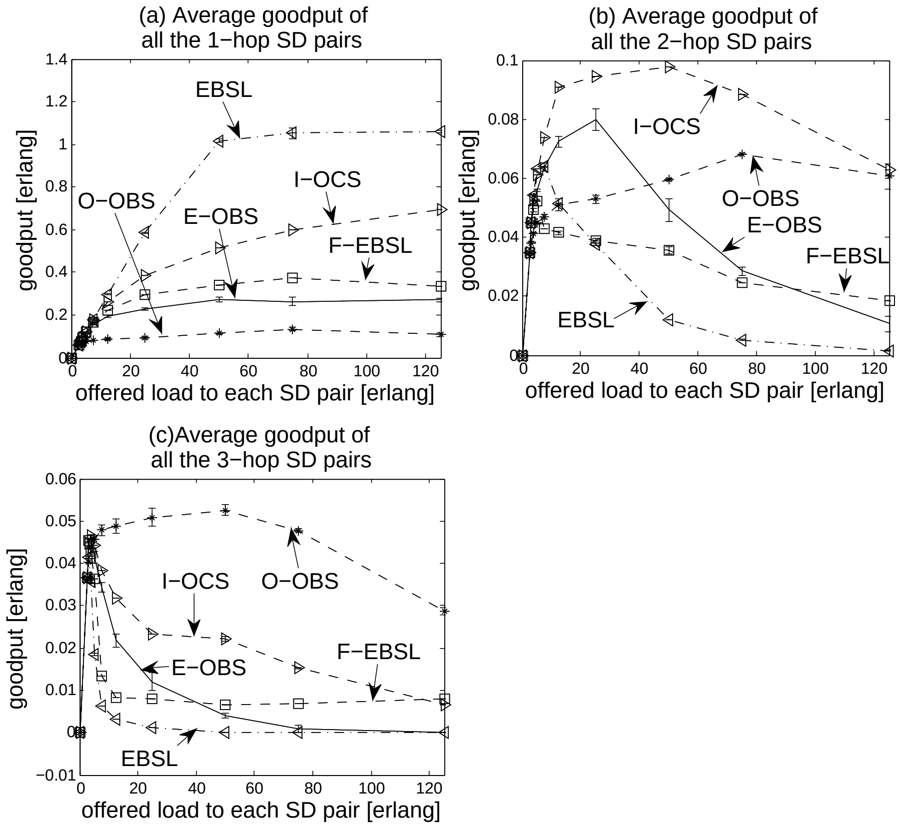

Figure 11: (a) Average goodput of all the 1-hop SD pairs, (b) Average goodput of all the 2-hop SD pairs and (c) Average goodput of all the 3-hop SD pairs in the NSFNet for O-OBS, E-OBS, EBSL, F-EBSL and I-OCS.

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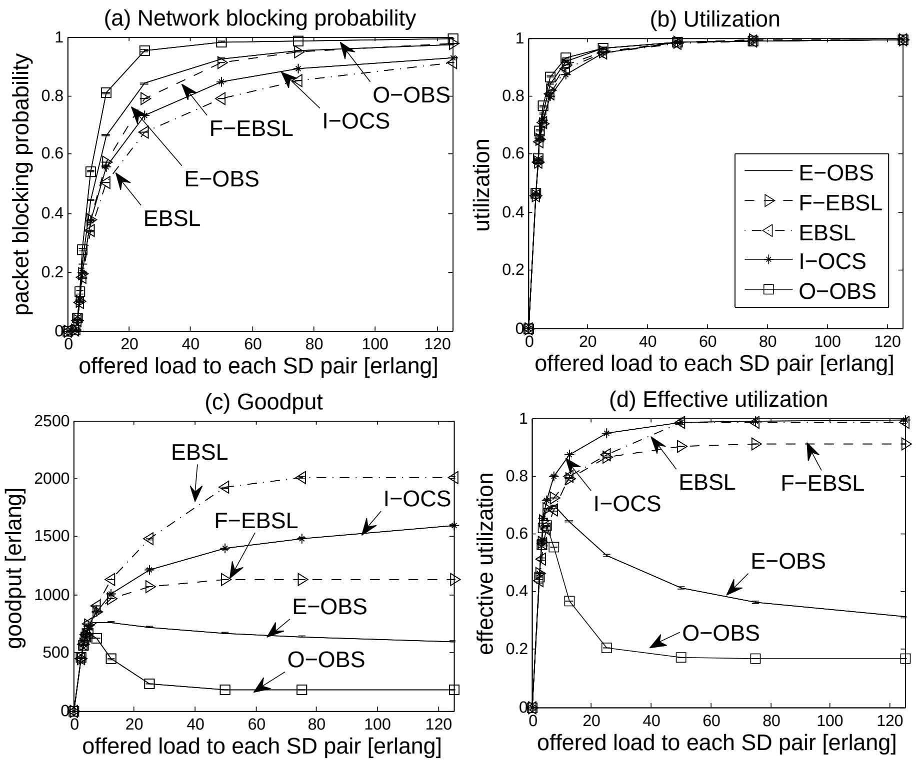

Figure 12: The blocking probability, utilization, goodput and effective utilization in the NSFNet for the networks with O-OBS, E-OBS, EBSL and F-EBSL.

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