Evaluating OBS by Effective Utilization

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***Abstract*—In optical burst switching (OBS) networks, bursts may be dumped before they reach their destinations due to contention. Accordingly, we classify trunk utilization into effective and ineffective utilizations used for bursts that reach and do not reach their destinations, respectively. As a benchmark for OBS, we consider an idealized version of optical circuit switching (OCS), designated I-OCS, that does not incur ineffective utilization. In this paper, we study the efficiency of OBS versus I-OCS networks for selected scenarios to facilitate the understanding of performance implications of effective and ineffective utilizations.**

***Index Terms*—blocking probability, circuit switching, burst switching, Erlang fixed-point approximation, utilization**

I. INTRODUCTION

Optical burst switching (OBS) [1] is a technology that facilitates one-way dynamic resource reservation of data flows suited to all-optical networks. In OBS networks, data-packets with the same destination are aggregated at ingress nodes and form bursts. A control packet is sent ahead of a burst to reserve wavelength channels along the burst transmission path. Since the wavelength channels are reserved hop by hop, the reservation time ahead of data transmission is generally shorter than in an end-to-end reservation scheme used in optical circuit switching (OCS). Another benefit of OBS over OCS is that OBS lightpath is fully utilized during a burst transmission which may not be the case in OCS.

OBS is often compared to various circuit switching alternatives [2]–[5], including OCS and optical flow switching (OFS) [5], where end-to-end network resources are reserved in advance, so that payload sent always reaches its destination. In OBS, on the other hand, a burst may be blocked and dumped after utilizing some network resources.

Previous performance studies of OBS networks have focused on blocking probability, e.g. [6], [7], defined as a ratio of the bursts that are lost to the bursts that are sent, and utilization, e.g. [3], [8], defined as the average proportion (over all trunks) of busy channels out of the total number of channels in a trunk. In this paper, to gain insight into the efficiency effects of topology and traffic parameters, we view OBS utilization as composed of two parts: effective and ineffective utilizations, distinguishing between channels used by bursts that eventually reach their destinations, and bursts that are dumped before reaching their destinations, respectively. This is illustrated in Fig. 1 where a 4-node 3-trunk network with two channels per trunk is depicted in which bursts are designated by their end nodes. Burst AD (sent from Node A to D), which utilizes a channel in trunks 1 and 2, is blocked and dumped in Node C because the only two channels in Trunk 3 are already occupied by bursts CD and BD. In this example, Trunk 1 is 50% ineffectively utilized. Trunk 2 is 50% effectively and 50% ineffectively utilized, and Trunk 3 is 100% effectively utilized.

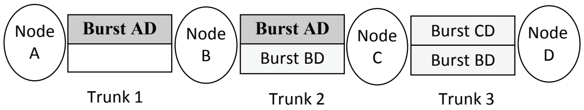

Fig. 1. Effective and ineffective utilizations in OBS.

As a benchmark for OBS performance, we use an idealized version of OCS, designated I-OCS, where we ignore the effect of the waste of utilization associated with the time a resource is being reserved until the first payload actually arrives. This wastage of OCS can be significant especially for circuits that their holding times are short, e.g., less than one round trip time. We also assume that I-OCS channels are fully utilized.

While both types of utilization compete for the same pool of resources and contribute to blocking probability, effective utilization translates into network goodput, but ineffective utilization does not. Accordingly, considering effective and ineffective utilizations can provide insight into OBS performance and efficiency. This is illustrated in this paper that discusses cases where OBS utilization comprises mainly effective utilization, so OBS performs close to its I-OCS benchmark, versus cases where ineffective utilization is significant and detrimental to efficiency.

II. NETWORK MODELING

As discussed, we consider an OBS network model and its I-OCS benchmark. A key difference between the two is that in OBS, the burst is transmitted hop-by-hop until it successfully reaches its destination or until it is blocked and dumped, while in I-OCS, it is not transmitted unless an end-to-end lightpath is available. Both models are characterized by a network that comprises a set of nodes $\alpha = \{1, \ldots, N\}$ connected by a set of trunks $\mathcal{J}$. Each 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.

Each unique pair of source and destination nodes form a directional source-destination (SD) pair, m. The set of all SD pairs in the network is denoted $\beta = \{1, 2, \ldots, N(N-1)\}$. We consider directional SD pairs, so $\{s,d\} \in \beta$ represents an SD pair with $s \in \alpha$ being the source and $d \in \alpha$ the destination, then $\{d,s\}$ and $\{s,d\}$ are two different elements in β. The offered traffic ρ_m [erlang] for each SD pair $m = \{s,d\} \in \beta$ is composed of bursts that follow a Poisson process. The burst lengths are exponentially distributed with unit mean. It is well known that the blocking probability of an M/G/k/k system is dependent only on the mean of the service time and it is insensitive to higher moments of the service time distribution. Kelly [9]

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shows that this insensitivity property applies to end-to-end blocking probability in I-OCS networks as the trunk capacity and traffic grows to infinity. Although this result has not been proven for OBS networks, numerical studies have provided evidence showing that the blocking probability results are not very sensitive to the shape of the burst length distribution [10].

In our OBS network model, at source node s, all bursts with destination node d are transmitted on the first trunk of the route $R(s,d)$. At each intermediate node, the burst is forwarded on the next trunk in route $R(s,d)$ until it reaches d. If the burst finds a trunk in $R(s,d)$, where all the wavelength channels are unavailable, the burst is blocked and cleared from the network. By comparison, in I-OCS, a burst transmission will not commence unless a wavelength channel is available on all trunk-hops between a source and its destination.

In our OBS model, we assume no guard bands between bursts, no offset effects, no specific OBS reservation protocols or scheduling algorithms, and no partial wavelength conversion. In the I-OCS network model, we ignore delays related to path set-up, reservation and propagation, and assume that the path holding time is used solely for the burst transmission. Finally, we note that the 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 on each intermediate trunk (excluding the first trunk) in a route.

III. PERFORMANCE EVALUATION

Given the limitations of simulations, we must resort to approximations in cases where the number of wavelength channels per trunk is large. To this end, we use the Erlang Fixed Point Approximation (EFPA) shown in [9] to be exact as the traffic and the number of channels per trunk approaches infinity.

Calculation of blocking probability for EFPA begins by randomly choosing the initial blocking probabilities (Uniform[0,1)). We then solve a set of fixed-point equations by successive substitutions until convergence occurs. The result of the fixed-point equations is the blocking probability on each trunk, which is used to calculate the end-to-end blocking probability for each SD pair. The average blocking probability, over all SD pairs, is the average of the end-to-end blocking probability for all SD pairs, weighted by their offered traffic.

The fixed-point equations for EFPA comprise two sets of equations. One set of equations is used to calculate the offered load on each trunk, using the current estimate of the blocking probability. The second set of equations is used to calculate a new estimate of the blocking probability, using the estimate of offered load obtained using the first set of equations. For more details on application of EFPA to fixed routing networks see [11] for I-OCS networks and [6], [12] for OBS networks.

In the following we present the equations we use to calculate goodput, utilization, effective utilization and ineffective utilization. Defining goodput as traffic that successfully reaches its destination, we consider in this paper the measures that distinguish between resources used for goodput and resources used for traffic that is eventually dumped. For every $m \in \beta$, let $g(m)$ be the goodput of SD pair m. It is obtained by

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

where $k(m)$ is the last trunk in the route of m, $a_{k(m)}$ is the offered load of m [erlang] that is offered to trunk $k(m)$ and $b_{k(m)}$ is the blocking probability of trunk $k(m)$.

Let g_n be the network goodput (also known as throughput), which is the total goodput of all SD pairs. That is,

$$g_n = \sum_{m \in \beta} g(m). \tag{2}$$

The utilization $U(j)$ of trunk j is obtained by

$$U(j) = \frac{1}{C_j} \sum_{i=0}^{C_j} i \times q_j(i), \tag{3}$$

where $q_j(i)$ is the steady-state probability of i busy channels on trunk j and C_j is the number of channels on trunk j.

Define the indicator function $d(j,m)$ by

$$d(j,m) = \begin{cases} 0 & \text{trunk } j \text{ not in the route of SD pair } m, \\ 1 & \text{trunk } j \text{ in the route of SD pair } m. \end{cases} \tag{4}$$

Accordingly, let $EU(j)$ be the effective utilization of trunk j which is the part of the utilization of trunk j used for goodput. It is obtained by

$$EU(j) = \frac{1}{C_j} \sum_{m \in \beta} d(j,m) \times g(m). \tag{5}$$

Also, define ineffective utilization $IU(j)$ of trunk j as the part of the utilization of trunk j used for traffic that is dumped before it reaches its destination. It is obtained by

$$IU(j) = U(j) - EU(j). \tag{6}$$

Then, network utilization U_n, effective utilization EU_n and ineffective utilization IU_n are the averages of trunk utilization, trunk effective utilization and trunk ineffective utilization, over all trunks, respectively. They are obtained by,

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

$$EU_n = \frac{1}{G} \sum_{j \in \mathcal{J}} EU(j), \tag{8}$$

and

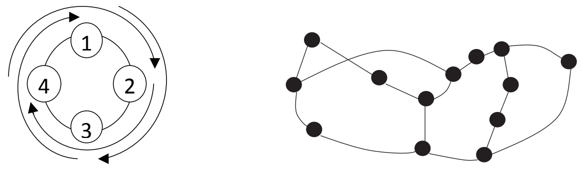
$$IU_n = \frac{1}{G} \sum_{j \in \mathcal{J}} IU(j), \tag{9}$$

where G is the number of uni-directional trunks in $\mathcal{J}$.

IV. NUMERICAL RESULTS

In this section, using numerical results over a wide range of parameters, we illustrate how effective and ineffective utilizations affect OBS efficiency and how it compares to I-OCS. To this end, we use the 4-node ring network and the 13-node NSFNet topologies depicted in Fig. 2. We use fixed routing based on shortest path for each network. The SD pairs selected in the 4-node ring network are 1→3, 2→4, 3→1 and 4→2, and the 2-hop path for each SD pair is as shown in

Fig. 2 (a). For the 13-node NSFNet, we choose all possible SD pairs where shortest-path ties are broken randomly. The results are mainly based on simulations unless the running times are prohibitive in which case EFPA is used. 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. In any case, the length of the confidence intervals is always less than 10% of the mean value measured.



(a) 4-node ring

(b) 13-node NSFNet

Fig. 2. The 4-node ring and 13-node NSFNet topologies.

Considering first the 4-node ring topology, we begin with a scenario where the network is dimensioned based on maximum of 0.001 blocking probability for any SD pair. The results are provided in Fig. 3. In particular, for the given number of channels per trunk (x-axis), we increase the traffic uniformly in all SD pairs as long as the blocking probability does not exceed 0.001 for any SD pair. Then we compute the network utilization achieved (y-axis). Since blocking probability is small, the OBS network ineffective utilization is low, so the performance of OBS is expected to be close to that of I-OCS [8], as seen in Fig. 3. We also observe that the OBS and I-OCS achievable network utilizations increase with the number of channels per trunk. Because in the present case, the offered load is equal for all SD pairs and also for all trunks in the network, all SD pairs reach 0.001 blocking probability together, and the network utilization can reach close to 100% as the number of channels per trunk increases. This is consistent with known results under critical loading conditions [13], [14]. Note that simulation results confirm the EFPA results up to 1000 channels per trunk as shown in Fig. 3. Beyond that point, we rely solely on EFPA results, which experience shows (including the comparison made here) that they are more and more accurate as the number of channel per trunk increases.

A very different picture emerges if we keep increasing the offered load without capping the blocking probability, as shown in Fig. 4. With increasing load, in OBS, we observe goodput collapse. For I-OCS, we do not see this phenomenon, as the goodput asymptotically approaches the available capacity. For OBS, as long as the blocking probability is negligible, its effective utilization and goodput increase with the load as in I-OCS. Then, as the load keeps increasing, the blocking probability, see Fig. 4 (c), and the ineffective utilization keep increasing. Since effective and ineffective utilizations compete on the same resource, increase of ineffective utilization causes reduction of effective utilization, see Fig. 4 (b), which leads to goodput degradation as shown in Fig. 4 (a). Also observe from Fig. 4, that the difference between OBS and its I-OCS benchmark are far wider in terms of goodput and effective utilization than they are in terms of blocking probability. Clearly, effective utilization and goodput are important performance measures for OBS networks.

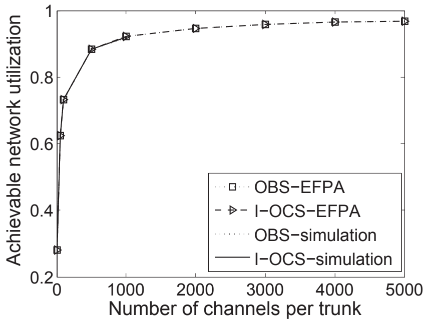


Fig. 3. Achievable network utilization for 4-node ring network for OBS and I-OCS, with blocking probability per SD pair limited to 0.001.

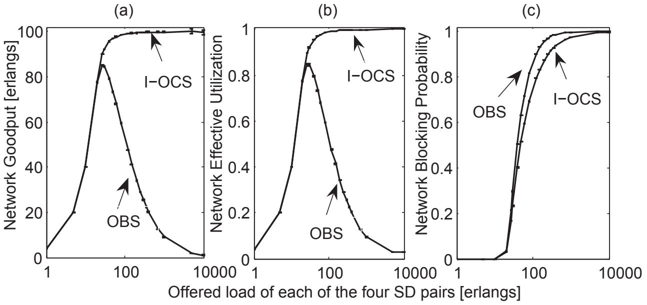


Fig. 4. (a) Network Goodput (b) Network Effective Utilization and (c) Network Blocking Probability versus offered load for the 4-node ring network with 50 channels per trunk.

For the 4-node ring network, when we set the same capacity for each trunk, the same offered load and the same number of path hops for each SD pair, then the traffic is the same on each trunk and for each SD pair. This avoids unbalanced load and regional contentions. This special case possesses the following two properties.

1) The network effective utilization is equal to the effective utilization of each individual trunk.
2) The goodput as a proportion of the maximum achievable goodput is equal to the network effective utilization.

Property 1 is clear as the network effective utilization is the average of the individual trunk effective utilizations which are all equal. To show Property 2, let C be the number of channels per trunk, let ρ be the offered load [erlang] of each SD pair, and let b be the overall blocking probability which in this case is also the blocking probability for each SD pair. The goodput in this case is $4(1-b)\rho$ and the maximum achievable goodput is $4(1/2)C = 2C$. The ratio between the two is $2(1-b)\rho/C$ which is equal to a trunk effective utilization (because each trunk is shared equally among the two SD pairs that use it), and by Property 1, it is equal to the network effective utilization. The latter is illustrated by Fig. 4 (a) and (b), where the maximum achievable goodput is $2 \times 50 = 100$.

To demonstrate the effect of traffic parameters on effective utilization and goodput, note that if we consider the 4-node topology with SD pairs: 1→2, 2→3, 3→4 and 4→1, we obtain a trivial case, where each SD pair is 1-hop behaving like I-OCS, so no ineffective utilization is created and the curves of OBS and I-OCS will overlap.

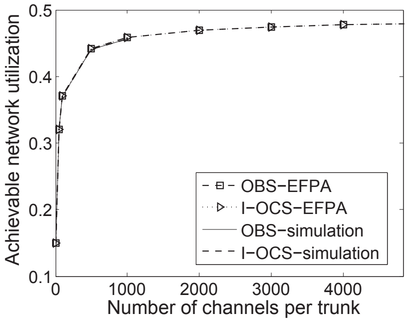


Fig. 5. Achievable utilization for OBS and I-OCS over NSFNet with blocking probability per SD pair limited to 0.001.

In the case of NSFNet, for the scenario where the blocking probability is limited to 0.001, the network utilization behavior of OBS relative to I-OCS, as shown in Fig. 5, is similar to the case of the 4-node ring topology except that the network utilization in NSFNet is significantly lower for cases with many channels per trunk.

Unlike the 4-node ring case, where the shortest path routing strategy also gives load balancing, using shortest path in NSFNet does not. Then as we stop increasing the offered load the moment the blocking probability of any SD pair reaches 0.001, different blocking probabilities for different SD pairs and different trunks are obtained causing the NSFNet to have low utilization on some trunks while others may be highly loaded [8]. Other OBS routing methods, e.g. deflection routing [10], may somewhat balance the load and improve performance and efficiency but may also have adverse effect due to the use of longer routes. Note that again simulation results confirm the EFPA results up to 1000 channels per trunk.

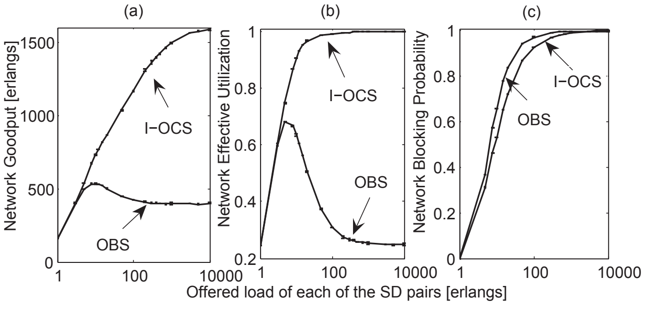


Fig. 6. (a) Network Goodput (b) Network Effective Utilization and (c) Network Blocking Probability versus offered load for NSFNet with 50 channels per trunk.

Interestingly, as shown in Fig. 6, although the unbalanced NSFNet also exhibits OBS goodput degradation with increased load, it is more resilient to high load than the 4-node case. This surprising resiliency can be explained as follows. In NSFNet, some of the SD-pair paths are long and others are short (as short as 1-hop), and the long ones are disadvantaged under heavy load. As mentioned, 1-hop SD pairs behave like I-OCS, so their blocking does not cause ineffective utilization. Then, under extremely heavy traffic (recall that there are 50 channels per trunk so the offered load of 1000 erlangs per SD pair is 20 times the trunk capacity) most of the successfully transmitted bursts are of 1-hop SD pairs that guarantee a certain level of effective utilization and some of the 1-hop SD pairs still experience high goodput independent of the increased load.

Notice also that in NSFNet, while the effective utilization of I-OCS quickly reaches a near unity level, the growth of I-OCS goodput is far slower. This is because the proportion of the 1-hop traffic increases with the offered load, which increases goodput while the network utilization remains near unity.

V. CONCLUSIONS

We have illustrated that effective and ineffective utilizations are key factors affecting performance and efficiency of OBS networks. They explain a level of OBS efficiency which almost equal to its I-OCS benchmark when the blocking probability is kept low and they also explain a weakness of OBS under high traffic load conditions leading to goodput degradation way below its I-OCS benchmark. By considering a 4-node ring topology, we have also demonstrated that very high network utilization is achievable by OBS if traffic is balanced, blocking probability is kept low and the number of channels per trunk is large. Understanding these key effects and in particular the adverse effect of ineffective utilization is important for understanding and improving performance and efficiency of OBS networks.

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