Performance evaluation of a bufferless OBS/OPS network with 1+1 path protection

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***Abstract*—In optical burst/packet switched (OBS/OPS) networks, bursts/packets may be dropped because of equipment failures. A widely used mechanism to protect a connection from a single-trunk-failure event is 1+1 path protection. We consider a bufferless OBS/OPS network with two types of users: premium (that receive 1+1 protection service) and regular (that do not receive such a service). We propose a fast and accurate approximation to evaluate the performance of such OBS/OPS network. The accuracy and scalability of the approximation and the effect of the proportion of the premium users in the network are discussed.**

***Index Terms*—burst loss ratio, optical burst/packet switching, 1+1 path protection, Erlang Fixed-Point Approximation.**

I. Introduction

During the last decade, we have witnessed an increasing number of Internet dependent mission-critical services that demand a high level of Quality of Service (QoS) in terms of performance (burst loss ratio) and survivability (availability). Burst loss ratio (BLR) is defined as the ratio of the bursts dropped in the network to the total number of bursts in the network. Throughout this paper, the term burst is used for a burst in OBS networks, or a packet in OPS networks, without loss of generality. As argued in [1], a high level of survivability is crucial for mission-critical-services. This calls for a differentiated QoS solution.

The 1+1 path protection mechanism is able to support the requirements of mission-critical-services [2]–[4]. In 1+1 path protection, data bursts are duplicated over two disjoint paths between an ingress and egress node in the network. Accordingly, 1+1 path protection is a resource demanding mechanism in its original form.

In this paper, we provide, for the first time, BLR evaluation of 1+1 path protection for an OBS network. In particular, we evaluate the BLR of a bufferless OBS/OPS network employing 1+1 path protection for its premium and regular users. Packets from premium users are aggregated to premium bursts, and duplicated over two disjoint paths on their ways to the destination node, while regular traffic is transmitted without any protection. Both the cases of full wavelength conversion and no wavelength conversion are considered. Note that the added redundancy from 1+1 path protection can be used to combat contentions in OBS/OPS. We derive a scalable and accurate approximation based on Erlang Fixed-point Approximation (EFPA) [5], [6] to evaluate the performance of premium and regular users. The approximations are validated using simulations for various load values on a small network (6 nodes) and larger networks (CORONET). The scalability of the approximation is demonstrated using the CORONET network (100 nodes, with up to 1000 channels per trunk).

None of the existing work that aimed to evaluate BLR of OBS with 1+1 protection ever considered a network setting. In [1], [7] the BLR is evaluated for a single source-destination pair based on given BLR parameters p_1 and p_2 for the two associated end-to-end paths, without specifying how p_1 and p_2 are obtained. Unlike [1], [7], we provide a network-wide analytical model which considers the interaction between different flows, which increases accuracy and usefulness.

II. The Model

Consider a bufferless OBS/OPS network described by a graph $G(\mathcal{N},\mathcal{E})$, where $\mathcal{N}$ is a set of n nodes and $\mathcal{E}$ is a set of e trunks. The nodes are designated $1,2,\ldots,N$, each of which is either an optical cross connect or an edge-router. Trunk $j \in \mathcal{E}$ is composed of f_j fibers and each fiber supports W_j wavelengths. In the case of full wavelength conversion, trunk $j \in \mathcal{E}$ carries $C_j = f_j W_j$ unidirectional wavelength channels, which are called *channels*. If all trunks have the same number of channels, then $C_j = C$ for all j. In the case of no wavelength conversion there are f_j, instead of $f_j W_j$, channels on each intermediate trunk (excluding the first trunk) in a route.

Let $\beta = \{1,2,\ldots,N(N-1)\}$ be the set of all directional source-destination (SD) pairs in the network. For SD pair $m \in \beta$, we choose the route with the least number of hops as the primary path $\mathbf{U}_m^{pri}$. 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 protection path $\mathbf{U}_m^{pro}$ for this SD pair, therefore $\mathbf{U}_m^{pri}$ and $\mathbf{U}_m^{pro}$ are edge-disjoint [8].

There are two types of traffic: premium traffic generated by premium users and regular traffic generated by regular users. The arrivals of premium bursts for each SD pair $m \in \beta$ follow a Poisson process with mean value λ_m^p. When a premium burst arrives at the ingress node, the node will send the burst to its primary path and a copy of the burst to its protection

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path simultaneously. The arrivals of regular bursts for each SD pair m follow a Poisson process with mean value λ_m^r. When a regular burst arrives at the ingress node, the node will send the burst only to its primary path for a given SD pair. When a burst arrives at the first trunk on its path, it will randomly select a free channel for transmission. We assume that the service times of both types of bursts are independent and exponentially distributed with mean $1/\mu$.

III. BLR Approximation

In this section, we describe our approximation based on EFPA for BLR evaluation of the 1+1 protection network in the case of no wavelength conversion. For each SD pair m, let $\rho_m^{pri} = \lambda_m^p/\mu$ and $\rho_m^{pro} = \lambda_m^p/\mu$ be the offered load from the premium users to the primary path and the protection path, respectively. Although ρ_m^{pri} and ρ_m^{pro} are dependent, we assume that they are mutually independent. Let $\rho_m^r = \lambda_m^r/\mu$ be the offered load from the regular users to the primary path of SD pair m. We also assume that the traffic offered to each trunk follows an independent Poisson process.

Let $R_j(w)$ be the ratio of the number of channels in wavelength w to the total number of channels in trunk j. Assume for each SD pair m, $\rho_m^{pri}(w) = \rho_m^{pri} \times R_{\mathbf{U}_m^{pri}(1)}(w)$, $\rho_m^{pro}(w) = \rho_m^{pro} \times R_{\mathbf{U}_m^{pro}(1)}(w)$ and $\rho_m^r(w) = \rho_m^r \times R_{\mathbf{U}_m^{pri}(1)}(w)$ are the traffic from the premium users offered to the primary path and the protection path for wavelength w and the traffic from the regular users offered to the primary path for wavelength w, respectively. Let $\mathbf{U}_m^{pri}(1)$ be the first trunk on the path $\mathbf{U}_m^{pri}$ and $\mathbf{U}_m^{pro}(1)$ the first trunk on the path $\mathbf{U}_m^{pro}$.

Then $a_j(w)$ the total traffic offered to wavelength w on trunk j is calculated by

$$\begin{aligned} a_j(w) = \sum_{m\in\beta} &\Big[I'(j,\mathbf{U}_m^{pri})(\rho_m^{pri}(w)+\rho_m^r(w)) \\ &\times \prod_{i\in\mathcal{E}} (1-I(i,j,\mathbf{U}_m^{pri})b_i(w))\Big] \\ &+ \sum_{m\in\beta}\left[I'(j,\mathbf{U}_m^{pro})\rho_m^{pro}(w)\prod_{i\in\mathcal{E}}(1-I(i,j,\mathbf{U}_m^{pro})b_i(w))\right], \end{aligned} \tag{1}$$

where $I(i,j,\mathbf{U})$ and $I'(j,\mathbf{U})$ are two indicators that

$$I(i,j,\mathbf{U}) = \begin{cases} 1, & \text{if } i,j\in\mathcal{E} \text{ and trunk } i \text{ strictly precedes} \\ & \text{(not necessarily immediately) trunk } j \\ & \text{along path } \mathbf{U} \\ 0, & \text{otherwise,} \end{cases}$$

and

$$I'(j,\mathbf{U}) = \begin{cases} 1, & j\in\mathbf{U} \\ 0, & \text{otherwise,} \end{cases}$$

and $b_i(w)$ is the BLR of wavelength w on trunk i which is obtained by Erlang-B formula

$$b_i(w) = \frac{a_i(w)^{f_i}/f_i!}{\sum_{n=0}^{f_i} a_i(w)^n/n!}. \tag{2}$$

By considering each wavelength separately, we maintain wavelength consistency for each SD path.

After that, the BLR B_m^r of the regular traffic and the BLR B_m^p of the premium traffic for SD pair m are obtained using the following equations:

$$B_m^r = \sum_{w=1}^{W_{\mathbf{U}_m^{pri}(1)}} R_{\mathbf{U}_m^{pri}(1)}(w)(1-\prod_{j\in\mathbf{U}_m^{pri}}(1-b_j(w))) \tag{3}$$

and

$$\begin{aligned} B_m^p = &\sum_{w_1=1}^{W_{\mathbf{U}_m^{pri}(1)}}\left[R_{\mathbf{U}_m^{pri}(1)}(w_1)(1-\prod_{j\in\mathbf{U}_m^{pri}}(1-b_j(w_1)))\right] \\ &\times \sum_{w_2=1}^{W_{\mathbf{U}_m^{pro}(1)}}\left[R_{\mathbf{U}_m^{pro}(1)}(w_2)(1-\prod_{i\in\mathbf{U}_m^{pro}}(1-b_i(w_2)))\right] \end{aligned} \tag{4}$$

Assume $p_{pri} = \rho_m^{pri}/(\rho_m^{pri}+\rho_m^r)$, then the average BLR in the network is

$$B_{network} = \sum_{m\in\beta}(p_{pri}\times B_m^p + (1-p_{pri})\times B_m^r). \tag{5}$$

Eq. (1) – (5) can also be used in the case of full wavelength conversion by using f_jW_j instead of f_j and without distinction to different wavelengths.

IV. Numerical Results and Discussion

In this section, we validate the proposed approximation based on a 6-node fully-meshed network, and the 100-node CORONET shown in Fig. 1, and then test the scalability based on the CORONET in both non-failure case and single-trunk-failure case. In the 6-node fully-meshed network, we select the protection paths to maintain network symmetry under symmetrical traffic. We then analyze the effect of the proportion of the premium users on the network performance. To limit excessive simulation times, we focus on traffic loads that result in BLR above 10^{-5}. Error bars for 95% confidence intervals based on Student's t-distribution are provided for all the simulation results. All the results are obtained using MATLAB software executed on a laptop with Intel® Core™ 2 Quad @ 2.9 GHz CPU, 8 GHz RAM and 64-bit operating system.

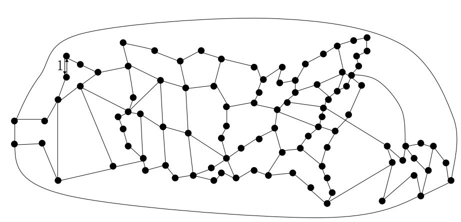

Fig. 1. Topology for the 100-node CORONET, where each solid line represents two unidirectional trunks in opposing directions.

A. *The case of full wavelength conversion*

We first examine the accuracy of the approximation in both non-failure and single-trunk-failure cases in the two networks. In the approximation, since we ignore the dependence with

ρ_m^{pri} and ρ_m^{pro}, the approximation underestimates the BLR. To test the effect of this error, we set the ratio $\rho_m^{pri}/(\rho_m^r+\rho_m^{pri})$ to 50% for $m \in \beta$, which implies $\rho_m^{pri} = \rho_m^{pro} = \rho_m^r$. The accuracy of the proposed approximation is illustrated in Fig. 2 for 6-node fully-meshed network, and in Fig. 3 for the CORONET. In the two networks, each trunk has 100 channels, and the traffic from the regular users to each SD pair is identical. We consider full wavelength conversion at each node.

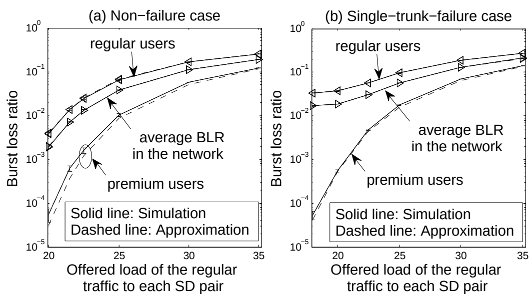

Fig. 2. BLR in the 6-node fully-meshed network for (a) the non-failure case and (b) single-trunk-failure case for full wavelength conversion.

From Fig. 2 (a), we observe that the approximation results for regular users are more accurate than those for premium users. This is because that the assumption that ρ_m^{pri} is independent of ρ_m^{pro} implies consideration of less burstiness in the approximation and therefore lower BLR. We also observe that when the traffic to each SD pair increases, the approximation results move closer to the simulation results. This is because we assume that the traffic to each trunk follows an independent Poisson process whereas in fact the traffic offered to a sequence of trunks on a path may be smoothed out when offered to one trunk due to blocking in the previous trunks. Ignoring this smoothing effect causes overestimation of BLR. When the traffic to each SD pair is low, the BLRs on different trunks are low, the error caused by the independence assumption of ρ_m^{pri} and ρ_m^{pro} dominates in the network so that the approximation underestimates the network BLR. Then as the traffic increases, the BLRs on different trunks increase, therefore the smoothing effect increases and cancels out the error caused by the independence assumption, thus the error of the approximation results decreases.

Comparing Fig. 2 (a) and Fig. 3 (a), we observe that for larger networks, the effect of the error caused by the independence assumption of ρ_m^{pri} and ρ_m^{pro} is reduced. This is because when the number of SD pairs in the network increases, each trunk contains more traffic flows from different SD pairs and this decreases the dependence between the traffic on different trunks. In other words, this diminishes the dependency created between traffic that flows through the primary path and the protection path of a given SD pair.

Since the network is symmetric, we randomly select one failed trunk in the six node fully-meshed network. The resulting BLR is shown in Fig. 2 (b). In the CORONET, the BLR results of Trunk 1 failure are shown in Fig. 3 (b). From Fig. 2 and Fig. 3, we observe that the proposed approximation is more accurate under single-trunk-failure case. This is because the bursts transmitted through the failed trunk are all

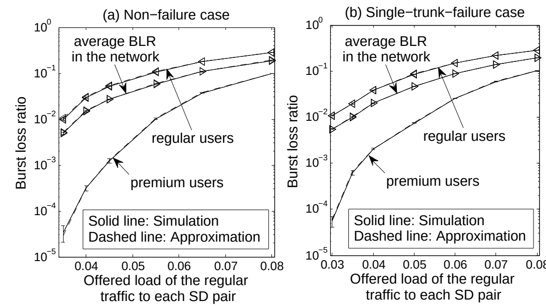

Fig. 3. BLR in the CORONET for (a) the non-failure case and (b) Trunk 1 failure case for full wavelength conversion.

blocked, the BLR for this corresponding source-destination pair depends only on the BLR of the protection path. Hence, the errors caused by the independence assumption of ρ_m^{pri} and ρ_m^{pro} for these bursts are eliminated.

B. The case of no wavelength conversion

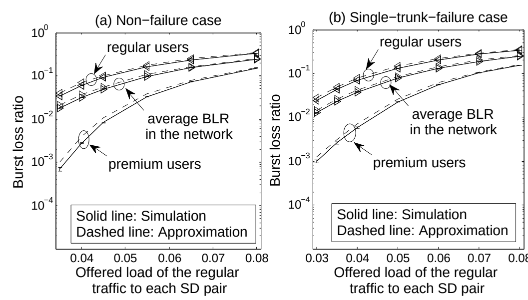

Fig. 4. BLR in the CORONET for (a) the non-failure case and (b) Trunk 1 failure case for no wavelength conversion.

We also examine the accuracy of the approximation in the case of no wavelength conversion using the CORONET. We assume each trunk has 4 different wavelengths and each wavelength has 25 channels. Other parameters are set as those used for the results presented in Fig. 3. The accuracy of the proposed approximation is illustrated in Fig. 4, where we observe that the approximation gives higher values than the simulation. This is because in the approximation an arriving burst first chooses an individual wavelength randomly (uniformly) and then it selects a random channel on this wavelength. However, in the simulation an arriving burst can choose among *all* available free channels on all wavelengths. Therefore, the approximation overestimates the network BLR. Note that in both the approximation and simulation, we maintain wavelength consistency for each SD path.

Comparing Fig. 4 and 3, we observe that full wavelength conversion reduces the network BLR by 74% and 23% when $\rho_m^r = 0.035$ erlang and $\rho_m^r = 0.08$ erlang under the non-failure case, respectively. Under the single-trunk-failure, full wavelength conversion reduces the network BLR by 55% and 21% when $\rho_m^r = 0.03$ erlang and $\rho_m^r = 0.08$ erlang, respectively.

C. Scalability of the proposed approximation

We examine the scalability of the approximation based on the CORONET in both non-failure case and single-trunk-failure case. We consider full wavelength conversion at each node. We set $\rho_m^{pri} = \rho_m^r$ for each $m \in \beta$ and the values of ρ_m^{pri} are set to be the same for all $m \in \beta$. Table I lists the times used by the approximation for one BLR calculation under the non-failure and the single-trunk-failure cases. We vary the number of channels per trunk to examine the scalability of the approximation in each case. The values of ρ_m^{pri} are chosen to keep the BLR of premium users around 0.05. We also investigate the time used by the approximation when the offered load in the network increases, as shown in Table II. We observe that the time used by the approximation increases when the offered load from the premium users increases. However, even for 1000 channels per trunk with high offered load from premium users, the approximation obtains one result in about 2.5 minutes. This is far less compared to a simulation which requires dozens of hours. This is especially important in optimal design problems that require many such BLR calculations to obtain the desired value.

TABLE I
TIME USED BY THE APPROXIMATION FOR ONE BLR CALCULATION IN THE CORONET WITH DIFFERENT NUMBER OF CHANNELS EACH TRUNK.

number of channels each trunk	ρ_m^{pri} for $m \in \beta$ [erlang]	running time for each BLR calculation [second]	error of the BLR approximation for the premium users
Non-failure case			
20	0.0111	4.24	4.37%
100	0.069	8.95	3.69%
500	0.362	31.17	2.79%
1000	0.73	75.40	2.58%
Single-trunk-failure case			
20	0.0109	3.41	3.96%
100	0.068	7.92	3.32%
500	0.357	28.88	2.47%
1000	0.722	72.33	2.36%

We also test the effect of the number of channels in each trunk on the accuracy of the approximation and the results are listed in Table I. The error [%] of the BLR approximation for the premium users equals to $100 \times [|(simulation\ BLR - approximation\ BLR)|/simulation\ BLR]$. We observe that when the number of channels in each trunk increases, the error of the BLR approximation for the premium users decreases under both non-failure and single-trunk-failure cases.

TABLE II
TIME USED BY THE APPROXIMATION FOR ONE BLR CALCULATION IN THE CORONET WITH C=1000 UNDER THE NON-FAILURE CASE.

ρ_m^{pri} for $m \in \beta$ [erlang]	BLR for the premium users	running time for each BLR calculation [second]
0.4	9.13×10^{-4}	8.36
0.5	0.0046	12.56
0.7	0.042	56.19
0.83	0.092	139.13

D. *Effect of the proportion of the premium users*

Fig. 5 shows the average BLR for the premium bursts and regular bursts for the 6-node fully-meshed network without failure when $\rho_m^{pri} + \rho_m^r = 13$ erlangs and the ratio $\rho_m^{pri}/(\rho_m^{pri} + \rho_m^r)$ is varied. We consider full wavelength conversion at each node, and each trunk has 20 channels. We observe that when the ratio $\rho_m^{pri}/(\rho_m^r + \rho_m^{pri})$ falls below a certain level (around 18%), premium bursts have a lower BLR than in the case without 1+1 protection. However, if this ratio is larger than that level, the premium users will suffer a high BLR even higher than in the case without protection (and without redundant bursts). Understanding the effects of this ratio is important in network design that aims to meet QoS requirement of the high priority users.

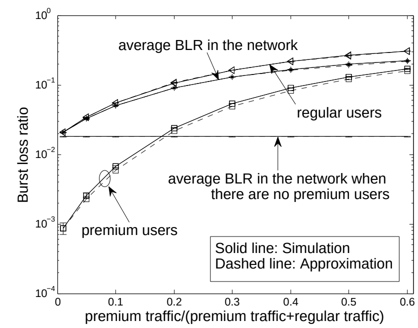

Fig. 5. Burst loss ratio for different users in the case of the 6-node fully-meshed network for the scenario where $\rho_m^r + \rho_m^{pri}$ is fixed at 13 erlangs for $m \in \beta$ and the ratio $\rho_m^{pri}/(\rho_m^{pri} + \rho_m^r)$ is increased.

V. CONCLUSION

In this paper, we have proposed a fast and accurate approximation to evaluate the burst loss ratio in 1+1 protection bufferless OBS/OPS networks with both premium users and regular users under non-failure and single-trunk-failure cases. Both the cases of full wavelength conversion and no wavelength conversion have been considered. We have demonstrated the accuracy and the scalability of the approximation, as well as discussed the effect of the proportion of premium users. We have observed that the proportion of premium users needs to be below a certain level in order to guarantee their QoS.

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