Evaluation of burst/packet loss ratio in a bufferless OBS/OPS network with 1+X path protection

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***Abstract*—The importance of avoiding burst/packet loss because of equipment failures, especially for critical-mission services, gives rise to a method known as 1+X path protection in optical networks. This method provides additional protection for premium (including emergency) services than the more common 1+1 path protection. In this paper, we consider a bufferless OBS/OPS network with two types of users: premium (that receive 1+X protection service) and regular (that do not receive such a service). We propose an analytical method based on Erlang Fixed-Point Approximation to evaluate the burst/packet loss of such OBS/OPS network. We demonstrate numerically the accuracy of the approximation, and also the effect and implications of the proportion of the premium traffic as X increases.**

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

I. Introduction

With the ever-increasing dependence on the Internet, the number of mission-critical services requiring a high level of Quality of Service (QoS) also increases [1]. Such key services need to be protected in cases of cascading or simultaneous failures in telecommunications networks due to natural or human made causes, e.g. [2]. An important performance measure in Optical Burst Switched (OBS) networks is the *burst loss ratio* (BLR) defined as the ratio of the bursts dropped (dumped) to the total number of bursts generated in the network. An equivalent term is *packet loss ratio* for Optical Packet Switched (OPS) networks. As in [3], for sake of simplicity of exposition, we will henceforth use the term *burst* for a burst in OBS networks, or a packet in OPS networks, without loss of generality. Yu *et al.* [4] proposed a 1+X protection mechanism where the ingress node sends 1+X identical copies of a burst over 1+X disjoint paths in order to protect the network from at most X simultaneous link (trunk) failures. The 1+X path protection approach is a generalization of the more common 1+1 path protection [5], where only two identical copies of each burst are sent over 2 disjoint paths.

In [3], we proposed a method based on Erlang Fixed-Point Approximation (EFPA) to evaluate the BLR in a network with 1+1 protection. This approximation was shown to be accurate in the case of full wavelength conversion, but not so accurate in the case of no wavelength conversion. In [6], EFPA was applied to OBS without projection.

The contribution of this paper is threefold. Firstly, we introduce a new EFPA-based method that improves the accuracy of [3], especially in the case of no wavelength conversion. Secondly, we extend the work in [3] from 1+1 protection to 1+X protection, and thirdly, we provide discussions on QoS effects associated with varying parameters such as X and the proportion of premium traffic. The accuracy of the new approximation is validated. The results demonstrate that the new approximation is significantly more accurate than the one in [3] in the case of no wavelength conversion.

II. The Model

We consider a bufferless OBS/OPS network modeled by a graph $G = (V, E)$ comprising a set V of nodes and a set E of trunks. Accordingly, a node may represent an optical cross connect, an edge router or an optical switch. Trunk $j \in E$ is composed of f_j fibers where each fiber supports W_j wavelengths and each wavelength supports S_j sub-wavelength channels (e.g. TDM). For the case of full wavelength conversion, trunk $j \in E$ carries $C_j = f_j W_j S_j$ unidirectional channels. For the case of no wavelength conversion, a new burst will randomly select a free channel for transmission, and will use the same wavelength for its entire travel. In this case, we consider that $C_j = f_j S_j$ channels on each intermediate trunk (excluding the first trunk) in a route. If all wavelengths carry the same number of subwavelegth channels (S) and each fiber carries the same number of wavelengths (W) and each trunk has the same number of fibers (f), then in the case of full wavelength conversion, the total number of channels is the same on each trunk $C = fWS$, and in the case of no wavelength conversion $C = fS$ for each wavelength.

The set of all uni-directional source-destination (SD) pairs in the network is denoted β. For each SD pair $m \in \beta$, the primary path $\mathbf{U}_m^{pri}$ is chosen to be the route with the least number of hops. We then consider a new topology in which the trunks of the primary path are excluded, and the first protection path $\mathbf{U}_m^{pro_1}$ for this SD pair is chosen to be the least-hop route in the new topology. Next, considering another new topology where the trunks of the primary path and the first protection path are excluded to find the second protection path $\mathbf{U}_m^{pro_2}$. Finally, the above procedure is repeated until all the X protection paths are found such that the primary path and all the protection paths are edge-disjoint [7].

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We consider two types of services: premium and regular that generate two types of traffic streams of premium and regular bursts. For each SD pair $m \in \beta$, the premium and the regular bursts arrive following Poisson processes with rates λ_m^p and λ_m^r, respectively. When a premium burst is generated, the ingress node will send the burst through its primary path and a copy of the burst through each protection path simultaneously. However, for a new regular burst, the ingress node will send the burst only through its primary path to its destination. The service times of all bursts are assumed to be independent and exponentially distributed with mean $1/\mu$.

III. BLR Approximation

We first describe here in detail our method of BLR approximation for the 1+X protection network focusing on the case of no wavelength conversion. Then we show how the BLR is approximated for the case of full wavelength conversion.

For each SD pair $m \in \beta$, the premium offered traffic to the primary path and to the nth protection path are $\rho_m^{pri} = \lambda_m^p/\mu$ and $\rho_m^{pro_n} = \lambda_m^p/\mu$, respectively. Although the traffic streams to the primary and the protection paths are dependent, we assume in our approximation that they are mutually independent. In a similar way, we denote by $\rho_m^r = \lambda_m^r/\mu$ the regular offered traffic to the primary path of SD pair m. The traffic streams to all the different paths are assumed under the EFPA approximation to follow independent Poisson processes.

In [3], the BLR approximation overestimates the network BLR, because in [3] we assumed that a newly generated burst will randomly chooses one wavelength among all the wavelengths in the first trunk on its path. Then if all the channels in that wavelength are busy, the burst is blocked without trying other wavelengths that may have available channels. However, as expected from a real system, assignment of a new burst is based on choosing a channel among all available free channels in the trunk so that only if all the channels of all wavelengths are busy, the burst is blocked from that trunk. In our simulations this choice of a channel is made based on a uniformly random choice among all available channels. Here, we introduce a new modeling approach that captures this realistic characteristic more accurately than the assumption of [3]. This is done by enabling a newly generated burst to select a channel among all available channels as described below.

Let $R_j(w)$ be the ratio of the number of channels of wavelength w to the total number of channels in trunk j. Since S_j is the same for each wavelength in trunk j, we have $R_j(w) = 1/W_j$. In the approximation, we first consider an approach where a new burst arriving at the first trunk j of a path randomly selects a channel with probability $R_j(w)$ for wavelength w. If all the channels of the selected wavelength are busy, then the new burst is deflected to other wavelengths until it finally finds a free channel in one wavelength, or it is blocked from the network if all the channels in all the wavelengths are busy. Then we calculate the BLR using this new modeling approach and consider this value as the BLR approximation of the network.

Let $\mathbf{U}_m^{pri}(1)$ be the first trunk on the path $\mathbf{U}_m^{pri}$ and $\mathbf{U}_m^{pro_n}(1)$ the first trunk on the path $\mathbf{U}_m^{pro_n}$, $n = 1,2,\ldots,X$. The premium traffic of SD pair m offered to the primary path and the nth protection path for wavelength w are obtained by

$$a_m^{pri}(w) = \rho_m^{pri} \times PI(\mathbf{U}_m^{pri}(1), w), \tag{1}$$

and

$$a_m^{pro_n}(w) = \rho_m^{pro_n} \times PI(\mathbf{U}_m^{pro_n}(1), w), \tag{2}$$

respectively. The function $PI(j,w)$ represents the ratio of the traffic offered to wavelength w on trunk j to the total traffic offered to trunk j. It is defined in (8) below, where $b_j(w)$ is the BLR of wavelength w and WA_j is the set of wavelengths on trunk j. The traffic from the regular users of SD pair m offered to their primary path for wavelength w is obtained by

$$a_m^r(w) = \rho_m^r \times PI(\mathbf{U}_m^{pri}(1), w). \tag{3}$$

Then $\bar{a}_j(w)$, the total traffic offered to wavelength w on trunk j is obtained by

$$\begin{aligned} \bar{a}_j(w) = & \sum_{m\in\beta} \big[I'(j,\mathbf{U}_m^{pri})(a_m^{pri}(w) + a_m^r(w)) \\ & \times \prod_{i\in E} (1 - I(i,j,\mathbf{U}_m^{pri})b_i(w))\big] \\ & + \sum_{m\in\beta}\sum_{n=1}^{X} \big[I'(j,\mathbf{U}_m^{pro_n})a_m^{pro_n}(w) \\ & \times \prod_{i\in E} (1 - I(i,j,\mathbf{U}_m^{pro_n})b_i(w))\big], \end{aligned} \tag{4}$$

where $I(i,j,\mathbf{U})$ and $I'(j,\mathbf{U})$ are indicator functions defined by

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

and

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

and $b_i(w)$ is obtained by Erlang-B formula

$$b_i(w) = \frac{\bar{a}_i(w)^{f_i}/f_i!}{\sum_{n=0}^{f_i} \bar{a}_i(w)^n/n!}. \tag{5}$$

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

Next, the BLR values B_m^r and B_m^p of the regular and premium traffic, respectively, for each SD pair $m \in \beta$ are obtained using (6) and (9) as follows.

$$B_m^r = \sum_{w=1}^{W_{\mathbf{U}_m^{pri}(1)}} R_{\mathbf{U}_m^{pri}(1)}(w)(1 - \prod_{j\in\mathbf{U}_m^{pri}} (1 - b_j(w))) \tag{6}$$

Then the average BLR in the network is

$$B_{network} = \frac{\sum_{m\in\beta} (\rho_m^{pri} \times B_m^p + \rho_m^r \times B_m^r)}{\sum_{m\in\beta} (\rho_m^{pri} + \rho_m^r)}. \tag{7}$$

Eqs. (1) – (9) can also be used in the case of full wavelength conversion by using $f_jW_jS_j$ instead of f_jS_j and without distinction to different wavelengths.

$$PI(j,w) = R_j(w) + \sum_{w_1 \in WA_j \setminus \{w\}} \frac{R_j(w_1)b_j(w_1)R_j(w)}{[1-R_j(w_1)]} + \sum_{w_1 \in WA_j \setminus \{w\}} \frac{R_j(w_1)b_j(w_1)}{[1-R_j(w_1)]} \sum_{w_2 \in WA_j \setminus \{w,w_1\}} \frac{R_j(w_2)b_j(w_2)R_j(w)}{[1-R_j(w_1)-R_j(w_2)]} + \cdots$$
$$+ R_j(w) \sum_{w_1 \in WA_j \setminus \{w\}} \frac{R_j(w_1)b_j(w_1)}{[1-R_j(w_1)]} \cdots \sum_{w_{W_j-1} \in WA_j \setminus \{w,w_1,\cdots,w_{W_j-2}\}} \frac{R_j(w_{W_j-1})b_j(w_{W_j-1})R_j(w)}{R_j(w)} \tag{8}$$

$$B_m^p = \sum_{w_1=1}^{W_{\mathbf{U}_m^{pri}(1)}} R_{\mathbf{U}_m^{pri}(1)}(w_1)\Big(1 - \prod_{j \in \mathbf{U}_m^{pri}} (1-b_j(w_1))\Big) \prod_{n=1}^{X} \sum_{w_2=1}^{W_{\mathbf{U}_m^{pron}(1)}} \left[R_{\mathbf{U}_m^{pron}(1)}(w_2)\Big(1 - \prod_{i \in \mathbf{U}_m^{pron}} (1-b_i(w_2))\Big) \right] \tag{9}$$

To solve equations (1) – (5), we use the iterative procedure commonly used for EFPA, where we firstly set initial values to all $b_j(w)$ (in our case, these initial values were set to zero), and then iteratively update $b_j(w)$ using (1) – (5). In each iteration, we firstly use (1) – (4) to calculate the offered load to each wavelength on each trunk, then by (5) obtain new values for $b_j(w)$. We repeat these iterations until all $b_j(w)$ converge. Finally, we use (6), (7) and (9) to obtain the network BLR.

IV. Numerical Results and Discussion

In this section, we validate the proposed approximation based on a 10-node circular lattice network shown in Fig. 1 for both non-failure case and trunk-failure case. We then analyze the effect of the premium traffic proportion on the network performance when X increases. 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.

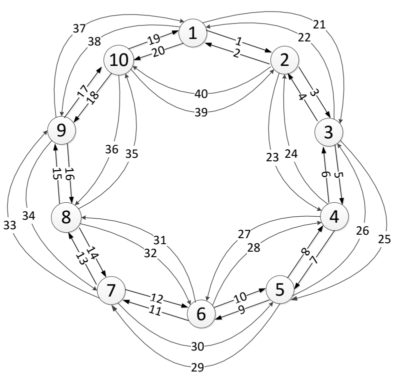

Fig. 1. Topology for the 10-node circular lattice network.

A. The case X=1

We first examine the accuracy of the new approximation compared to the one used in [3] for both non-failure and single-trunk-failure cases when $X = 1$. We set $f = 5$, $W = 4$, and $S = 5$. Namely, there are 5 fibers in each trunk. Each fiber carries 4 wavelengths and each wavelength is subdivided into 5 sub-wavelength channels, and the traffic from the regular users to each SD pair is identical. We also assume that 50% of the users are premium users, which implies $\rho_m^{pri} = \rho_m^{pro} = \rho_m^r$ for each $m \in \beta$. The results for the cases of full wavelength conversion and no wavelength conversion are shown in Figs. 2 and Fig. 3, respectively. For the single-failure-case, we assume that Trunk 1 fails, then 4 SD pairs (1→2, 1→4, 7→2 and 9→2) of regular users (their BLR will be 1) and 10 SD pairs (1→2, 1→3, 1→4, 1→10, 3→2, 7→2, 8→2, 9→2, 9→4 and 10→2) of premium users (their BLR will become larger than the non-failure case but less than 1) are affected. However, since there are totally 90 SD pairs in the network, and the proportion of the affected traffic in the network is not very large (less than 10%), the effect of the single trunk failure on the network BLR is not very large as shown in Figs. 2 and 3.

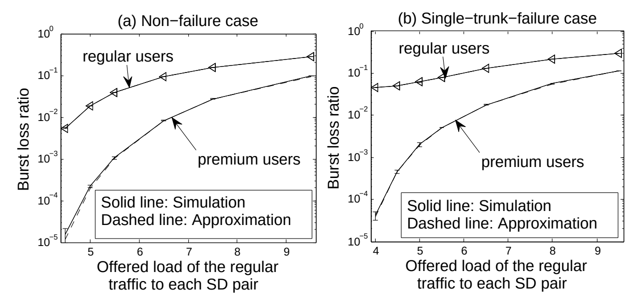

Fig. 2. BLR in the 10-node circular lattice network for (a) the non-failure case and (b) single-trunk-failure case for full wavelength conversion with $X = 1$.

Consider the full wavelength conversion case, both the new and the previous approximations are reduced to the same set of equations, giving the same results which are represented by the dashed lines in Fig. 2.

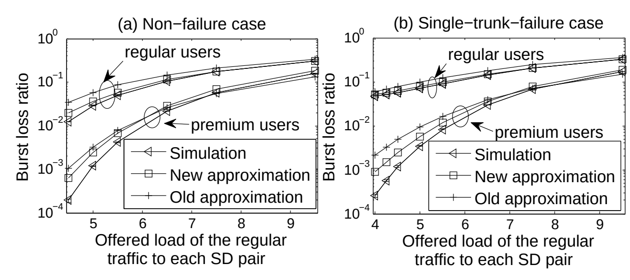

Fig. 3. BLR in the 10-node circular lattice network for (a) the non-failure case and (b) single-trunk-failure case for no wavelength conversion with $X = 1$.

From Figs. 2 and 3, we observe that under the full wavelength conversion case, the two approximations are very accurate. However, under no wavelength conversion, the new approximation is far more accurate than that of [3]. This is because in the new approximation, a new burst is blocked only if all the channels on all wavelengths are busy. This makes our new modelling approach work more like the real system than that of [3] as discussed in Section III.

B. The case $X > 1$

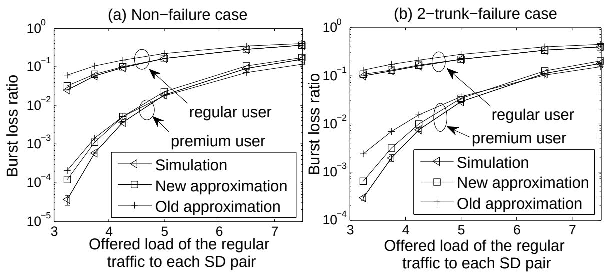

Fig. 4. BLR in the 10-node circular lattice network for (a) the non-failure case and (b) two-trunk-failure case for no wavelength conversion with $X = 2$.

We also examine the accuracy of the new approximation when $X > 1$ in the case of no wavelength conversion. The results for $X = 2$, where we assume that Trunks 1 and 20 fail, are shown in Fig. 4 and those for $X = 3$, where assume that Trunks 1, 20 and 21 fail, are shown in Fig. 5.

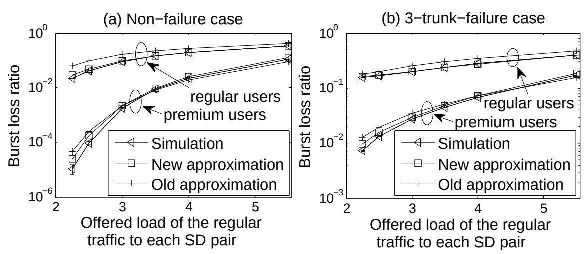

Fig. 5. BLR in the 10-node circular lattice network for (a) the non-failure case and (b) three-trunk-failure case for no wavelength conversion with $X = 3$.

From Figs. 4 and 5, we observe that as X increases, the approximation becomes more accurate. This is because when X increases, under the same traffic offered to the network, the actual number of bursts trying to access the network increases, which implies that the traffic in the network increases, leading to a reduction of the error of BLR. As discussed in [3], as traffic increases, the higher BLR increases the smoothness of traffic offered to trunks, which makes the Poisson assumption overestimate the BLR. This cancels out the BLR underestimation caused by the independence assumption of the traffic offered to the primary paths and the protection paths.

C. Effect of premium traffic proportion as X increases

Fig. 6 shows the average BLR for the premium and regular bursts without failure when $\rho_m^{pri} + \rho_m^r = 15$ erlangs and the ratio $\rho_m^{pri}/(\rho_m^{pri} + \rho_m^r)$ varies. We consider no wavelength conversion, again with $f = 5$, $W = 4$, and $S = 5$. All the results shown are obtained by discrete event simulation. We observe that when the ratio $\rho_m^{pri}/(\rho_m^r + \rho_m^{pri})$ is very small, the premium users have lower BLR with larger X. However, when the ratio $\rho_m^{pri}/(\rho_m^r + \rho_m^{pri})$ increases, the BLR of the premium users increases more rapidly with larger X. Therefore, when the ratio $\rho_m^{pri}/(\rho_m^r + \rho_m^{pri})$ increases, the premium users with 1+3 protection mechanism quickly reaches and exceeds the BLR level in the cases of 1+1, 1+2 and even no protection. This indicates that care should be taken when setting the value of X, because if X is set too large, the premium users may aggressively compete among themselves (consuming excessive amount of wavelength resources) and in this way they do not benefit from the high X values. For the regular users, increasing X always implies higher BLR. Understanding these effects are important in network design that aims to meet QoS requirements of high priority users.

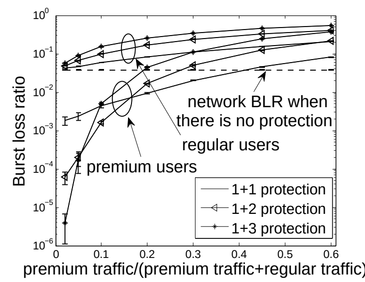

Fig. 6. BLR for different users for the scanario where $\rho_m^r + \rho_m^{pri}$ is fixed at 15 erlangs for $m \in \beta$ and the ratio $\rho_m^{pri}/(\rho_m^{pri} + \rho_m^r)$ is increased.

V. Conclusion

We have proposed a new, fast and accurate BLR approximation in 1+X protection bufferless OBS/OPS networks with both premium users and regular users under non-failure and failure cases. Both the cases of full wavelength conversion and no wavelength conversion have been considered. We have demonstrated that the new approximation is significantly more accurate compared to the existing approximation for the no wavelength conversion cases. We have also provided new results that demonstrate the effect of increasing X and the proportion of premium traffic on BLR of both types of users. We have observed that care should be taken in setting the value of X, as if it is set too high, the QoS of even the premium users may be adversely affected.

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