Analysis of Bufferless OBS/OPS Networks with Multiple Deflections

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***Abstract*—We develop a new analytical model for the estimation of blocking probabilities in OPS and OBS networks. The model is used to analyze the performance of a new deflection method that uses multiple wavelength channel reservation thresholds, and gives network designers greater control over the performance of the network. The accuracy of the analytical model is assessed using simulations.**

***Index Terms*—Erlang fixed-point approximation, blocking probability, optical burst switching, optical packet switching, network design.**

I. INTRODUCTION

ALL-OPTICAL networks are seen as a way to accommodate the continued exponential growth in Internet traffic [1], [2]. For all-optical networks to be feasible, they must be both stable and efficient. In current electronic router-based networks, buffering is used to resolve contention, which increases efficiency, and packets are dropped when a buffer overflows due to congestion, which ensures stability. Although there have been some improvements in optical buffering technologies [1], there remain significant size and energy consumption limitations [3]. We focus on a model of a bufferless all-optical switched network [4] that uses deflection routing with full wavelength conversion to resolve contention [5]–[7], and wavelength channel reservation to increase stability [5], [7].

We develop a new analytical model for the estimation of blocking probabilities in bufferless optical packet switching (OPS) [2] and optical burst switching (OBS) networks considering Just-In-Time (JIT) signaling [8]. We apply the Erlang fixed-point approximation (EFPA) [9] to packet and burst switched networks with deflections [5], [7]. Here we extend the model to analyze a deflection method that uses multiple wavelength channel reservation thresholds. We use the model to analyze the performance of a new deflection method that uses multiple wavelength channel reservation thresholds.

II. NETWORK MODEL

We consider a network that comprises N nodes 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. Therefore, a trunk carries $C_j = f_j w_j$ wavelength channels called *links*. In this paper we exclusively use the term "packets" to refer to both packets and bursts.

Each node transmits and receives packets from every other node in the network, with each unique transmit and receive pair of nodes forming an origin-destination (OD) pair, m. The set of all OD pairs in the network is denoted β. The traffic demand ρ_m between each OD pair $m \in \beta$ is composed of packets that have an independent and exponentially distributed inter-arrival time with mean $1/\rho_m$. The packet lengths are exponentially distributed with unit mean.

For each OD pair, one of the shortest routes is designated the primary route and the remaining routes are referred to as alternate routes. If a packet traverses a route and at a certain node, including the source node, all the links on the forward trunk of the route are unavailable, the packet is deflected onto an alternate route [6]. Preference is given to shorter routes followed by pre-assigned ordering. The pre-assigned order is chosen at random at the beginning and it remains unchanged. A packet is permitted to be deflected at most D times. A packet is considered blocked (discarded/lost) if it reaches a node where all output trunks are busy or the packet exceeds the allowable maximum number of deflections.

We assume that a packet only occupies one link at a time. This assumption has been shown to introduce minimal error [7]. We also assume there are no guard bands between packets [7]. The results presented in this paper are equally applicable to a network with no wavelength conversion which has $f_j w_j$, instead of f_j, fibers per trunk [10], but we do not consider partial wavelength conversion [11] or specific scheduling algorithms [12].

III. THE MULTIPLE THRESHOLD METHOD

Deflection routing with wavelength conversion has been shown to effectively resolve contention in high capacity all-optical networks [13]. However, deflection routing can cause network instability in packet switched networks during periods of high load [5], [6]. Wavelength channel (link) reservation, analogous to trunk reservation in circuit switched networks, increases stability in packet switched networks [5]. Unfortunately, link reservation also prevents deflected packets from utilizing the reserved links during periods of low load and thus increases blocking at low traffic loads. In this paper, we propose the use of multiple link reservation thresholds, which, relative to the single threshold approach, gives a network designer greater control over the performance of the network.

Link reservation gives packets that have experienced fewer deflections an equal or higher priority. In our network model, we set link reservation thresholds $T_j^k \le C_j$ on each trunk j with $T_j^0 = C_j$ and $T_j^{k+1} \le T_j^k$, $k \ge 0$. If the number of

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links occupied on trunk j is greater than or equal to T_j^k but less than T_j^{k-1}, only packets that have been deflected fewer than k times are permitted to use that trunk. If the number of occupied links on trunk j once again falls below T_j^k, packets that have been deflected up to k times are permitted to use that trunk. For example, if the number of occupied links i is such that $T_j^1 \leq i < T_j^0$ on trunk j, only packets that are undeflected are permitted to use that trunk. If a trunk has only $n < D$ thresholds, then $T_j^k = T_j^n, n \leq k \leq D$.

IV. PERFORMANCE ANALYSIS

In this section we outline a method to estimate the blocking probability in an OPS/OBS network with multiple link reservation thresholds. The method is an adaptation of Erlang fixed-point approximation (EFPA) [9] for packet switched networks. The calculation involves randomly choosing the initial blocking probabilities (Uniform[0, 0.1]) then iterating through the following three steps until convergence occurs.

A. Step One: Offered Loads

As before, the traffic demand, or offered load, of each OD pair m is given by ρ_m. Let $a_j^k(m)$ be the offered load of OD pair $m \in \beta$, with $k \in \{1, \ldots, D\}$ deflections, on trunk $j \in \mathcal{J}$. In addition, the probability that a packet with k deflections is blocked on trunk j is b_j^k. If the first trunk of the primary route between OD pair m is trunk i_1, then trunk i_1 is offered the full load of the OD pair, i.e. $a_{i_1}^0(m) = \rho_m$. The second trunk i_2 in the primary route is offered the carried load of the first trunk. The carried load is defined as the proportion of offered load that is not blocked. The offered load of OD pair m on the second trunk i_2 of the primary route $a_{i_2}^0(m) = \rho_m(1 - b_{i_1}^0)$.

On the other hand, due to congestion, packets are occasionally blocked on a trunk of the primary route and are deflected onto alternate trunks and routes. The set of alternative routes for a given packet is solely determined by the node that the packet has reached and its destination node. The load offered to the first trunk l_1 of the first choice alternative route is related to the load offered to the next trunk i on the primary route by $a_{l_1}^{k+1}(m) = a_i^k(m) b_i^k$, where k is the number of deflections prior to the latest deflection. Similarly, the load offered to the first trunk l_2 of the second choice alternative route is $a_{l_2}^{k+2}(m) = a_{l_1}^{k+1}(m) b_{l_1}^{k+1} = a_i^k(m) b_i^k b_{l_1}^{k+1}$.

B. Step Two: Blocking Probabilities

Let a_j^k be the offered load, with k deflections, on trunk j. The variables a_j^k and $a_j^k(m)$ are related by

$$a_j^k = \sum_{m \in \beta} a_j^k(m). \tag{1}$$

The link state probability $q_j(i)$ for each trunk $j \in \mathcal{J}$ and each state $i \in \{1, \ldots, C_j\}$ (i.e. i links occupied) is estimated by

$$q_j(i) = \left(\sum_{n=0}^{D} \mathbf{1}\left\{ T_j^n \geq i \right\} a_j^n \right) \frac{q_j(i-1)}{i} \tag{2}$$

where $\mathbf{1}\{\}$ is the indicator function and $q_j(0)$ is set such that $\sum_{i=0}^{C_j} q_j(i) = 1$ is satisfied. This is an M/M/k/k queue with the arrival rate modified such that arrival traffic is restricted to packets that satisfy the link reservation threshold requirements.

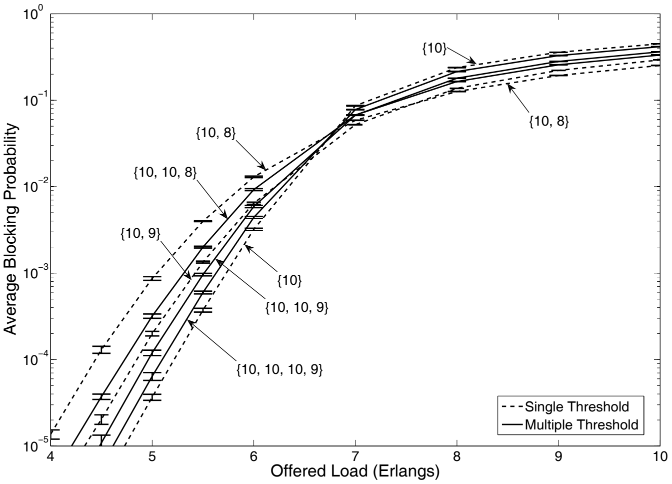

Fig. 1. Simulation results for a 6-node fully-meshed network.

The blocking probability, for packets with $k \in \{0, \ldots, D\}$ deflections, on trunk j is estimated by

$$b_j^k = \sum_{i=T_j^k}^{C_j} q_j(i). \tag{3}$$

C. Step Three: End-to-End Blocking Probabilities

Let $\mathcal{E}_m \subset \mathcal{J}$ be the set of trunks connected to the destination node of OD pair m. The end-to-end blocking probability of OD pair m, P_m is estimated by

$$P_m = 1 - \frac{\displaystyle\sum_{j \in \mathcal{E}_m} \sum_{k=0}^{D} a_j^k(m)(1 - b_j^k)}{\rho_m} \tag{4}$$

where $a_j^k(m)(1 - b_j^k)$ is the carried load of OD pair m, with k deflections, on trunk j. This expression summed over all the trunks connected to the destination node and all the possible deflections gives the total successful traffic.

The average blocking probability P is estimated by

$$P = \frac{\sum_{m \in \beta} \rho_m P_m}{\sum_{m \in \beta} \rho_m}. \tag{5}$$

V. NUMERICAL RESULTS

EFPA is known to introduce errors, due to the inherent assumption of independent Poisson packet arrivals at every node in the network [9]. In this section, we quantify the accuracy of our analytical method and analyze the benefits of our new deflection method using simulations.

Fig. 1 shows the average blocking probability (P) in a 6-node fully-meshed network for average offered loads (ρ_m) from 4 to 10 Erlangs, for a range of link reservation thresholds. Each trunk has 10 links and each node in the network forms an OD pair with every other node in the network, giving a total of 30 OD pairs. Packets are restricted to a maximum of three deflections. A link reservation threshold setting of {10,

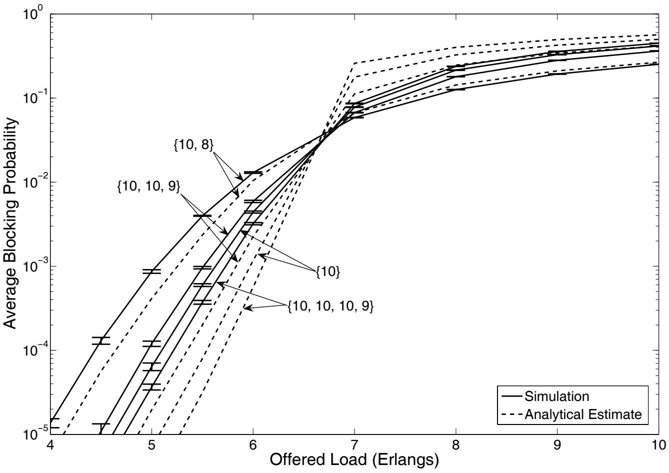

Fig. 2. Simulation results for a 6-node fully-meshed network as well as blocking probabilities approximated using our analytical model.

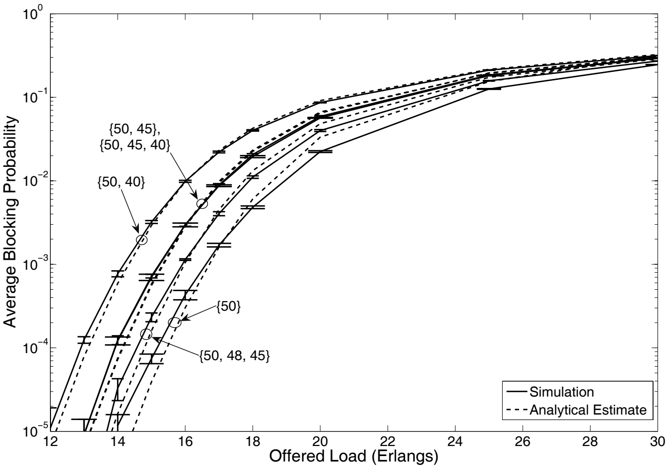

Fig. 3. Simulation results for a 13-node NSFNET as well as blocking probabilities approximated using our analytical model.

9, 8} corresponds to $T_j^0 = 10$, $T_j^1 = 9$ and $T_j^k = 8$, $k \geq 2$. If only a single link reservation threshold could be used for all deflected packets, the network designer would only be able to select one of $\{10\}$, $\{10, 9\}$ or $\{10, 8\}$. The results indicate that the ability to set multiple link reservation thresholds gives a network designer much greater control over the performance of a fully-meshed network. We note the inherent trade-off that increasing the link reservation threshold leads to lower blocking at low load but increased blocking at high load. The percentage of successful traffic deflected in our simulation was $\sim$1% with low link reservation thresholds and $\sim$3% with high link reservation thresholds.

Fig. 2 provides simulation and analytical results of the average blocking probability in a 6-node fully-meshed network for average offered loads from 4 to 10 Erlangs, for a selected number of link reservation thresholds. These results show that our method correctly predicts the order of the threshold settings. Our analytical estimate is not precise for high link reservation thresholds as there is a high percentage of deflected traffic, which increases the error caused by the Poisson and independence assumptions of EFPA.

Fig. 3 shows simulation and analytical results of the average blocking probability in a 13-node NSF network for average offered loads from 12 to 30 Erlangs for a selected number of link reservation thresholds. The NSF network topology simulated has 12 OD pairs, 32 trunks, 50 links per trunk and is further described in [6]. As before, packets are restricted to a maximum of three deflections. The results show that multiple link reservation thresholds give a network designer only slightly greater control over the performance of the network. Our simulations found that less than 1% of successful traffic undergoes more than one deflection. The small number of deflection opportunities limits the effect of multiple thresholds. The result that few deflections occur in the NSF network is consistent with those reported in [5], [7]. The lower proportion of deflected traffic in the NSF network ensures that our EFPA-based approximation is accurate.

VI. CONCLUSION

We have developed a new analytical model for bufferless OPS and OBS networks and demonstrated using simulations that the model is accurate if there is sufficient link reservation. We demonstrated that multiple link reservation thresholds give network designers more control over network performance.

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