A New Method for Blocking Probability Evaluation in OBS/OPS Networks with Deflection Routing

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***Abstract*— In this paper, we present a new method for the estimation of blocking probabilities in bufferless optical burst or packet switched networks. In such networks, deflection routing is used to reduce blocking probability. However, it requires certain wastage due to trunk reservation that must be used to avoid instability. We provide a wide range of simulation and numerical results to validate our new approximation method and demonstrate various effects on blocking probability and utilization, such as network size, trunk size, the maximal number of allowable deflections, and burst/packet length.**

***Index Terms*— Blocking probability, OBS, OPS, deflection routing, Erlang fixed-point approximation, overflow priority classification approximation, non-hierarchical networks.**

I. Introduction

As Internet traffic increases, the capacity of the networks that transport this traffic must also increase. Future all-optical networks are seen as a way to meet this growing demand [1], [2]. However, for all-optical networks to be economically feasible, improved methods of network dimensioning are required. A key component of network dimensioning is the accurate estimation of end-to-end blocking probability in the network [3]–[5]. In this paper, we present a new method for the estimation of end-to-end blocking probabilities in bufferless optical burst switched (OBS) [1] networks considering Just-In-Time (JIT) signalling [6], or optical packet switching (OPS) networks [2], [7]. The concepts of *blocking probability*, and end-to-end blocking probability, which are used interchangeably, are equivalent to the so-called *burst/packet loss ratio* [8], [9], defined as a ratio of the bursts/packets that are lost to the bursts/packets that are sent. The main cause of loss is lack of sufficient network resources as losses due to physical layer errors are negligible. Our new method is based on a recently published technique for estimation of blocking probabilities in general overflow loss networks [10]–[12].

The network model that we consider is sufficiently general to be applicable to a number of traffic management techniques shown to reduce blocking in all-optical networks. We include deflection routing [8], [13]–[23] and full wavelength conversion [24]. In addition, we include trunk reservation to account for some of the instability introduced by deflection routing [23], [25]. We focus on a model of a bufferless optical switched network [26]. The study of a bufferless optical switched network is important because although there have been some improvements in optical buffering technologies [1], significant size and energy consumption limitations remain [27]. On the other hand, the alternative of electronic buffering suffers from the drawback of energy intensive optical-to-electrical and electrical-to-optical conversion [27].

Henceforth, we will use the term *burst* to refer to both a burst in the context of bufferless OBS/JIT networks, and a packet in the context of OPS networks. In Section V-H.1, we demonstrate that the accuracy of our method is not significantly affected by the size of the burst/packet although long bursts introduce dependency between load on consecutive trunks which slightly increases the end-to-end blocking probability. This effect is not captured by our approximation which is therefore slightly more accurate for OPS than for OBS. Accordingly, we will henceforth use the term OBS to refer to both OBS/JIT and OPS.

Our analysis focuses on burst based networks [23], where each node only ensures that there is sufficient capacity on the next link in the route. Bursts that are blocked at nodes other than at their source node consume network resources before they are blocked and cleared from the system. The consumption of resources by blocked bursts has a non-negligible effect on the blocking probability of the network, particularly in networks with a high traffic load. This is unlike circuit-switched or optical circuit switched (OCS) networks, where the network ensures that there is sufficient capacity on all links in the route and reserves this capacity for the duration of the transmission [5], [12]. In OCS networks, the consumption of network resources by transmissions that are blocked is limited to the circuit set-up time and this wastage of network resources is negligible. This key difference between OCS networks and OBS networks means that analytical models for OCS networks cannot be directly applied to OBS networks and vice versa.

II. Blocking in Overflow Loss Networks

Calculating blocking probabilities in an overflow loss network model is an age-old tele-traffic problem that still remains pertinent to present-day all-optical networks. For example, an OBS network can be modeled as an *overflow* loss network if bursts are permitted to overflow to an alternate trunk when all channels comprising the first choice trunk are busy. This is referred to as deflection routing.

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The simplest possible overflow loss network comprises a first choice trunk and one or more alternate trunks. We refer to this as the *basic model*. The basic model serves as a building block for the modeling of large-scale networks that are interconnected via an arbitrary topology. In particular, the basic model can be straightforwardly incorporated into the Erlang fixed-point approximation to facilitate calculation of end-to-end blocking probabilities. Therefore, accurate calculation of end-to-end blocking probabilities in an overflow loss network hinges on accurate calculation of blocking in the basic model.

Blocking analysis of the basic model can be traced back to the work of Kosten [28] in 1937. Kosten derived the distribution of the number of busy channels on the first alternate trunk. Assuming without loss of generality that the mean burst size is equal to unity, bursts were assumed to arrive at the first choice trunk according to a Poisson process with rate a. The alternate trunk was assumed to comprise an infinite number of channels. Of particular interest was the mean $M = aE(a, N)$ and the variance $V = M\big(1-M+a/(N+1-a-M)\big)$ of this distribution, where N is the number of channels composing the first choice trunk and $E(a, N)$ denotes the Erlang-B formula.

More than ten years later, Brockmeyer [29] advanced one step further by deriving the distribution of the number of busy channels on the second alternate trunk, when the first alternate trunk now comprises a finite number of channels, K. Brockmeyer showed that the blocking probability on the first alternate trunk is given by the ratio $E(a, N + K)/E(a, N)$.

Generalizing the brute-force derivations of Kosten and Brockmeyer to a cascade comprising more than two alternate trunks is intractable. A seemingly tractable approach soon arose when it was recognized that the arrival of bursts on an alternate trunk was a renewal process. This suggested that existing analysis of the $GI/M/N/N$ queue could be invoked to calculate the blocking probability on the nth alternate trunk. Pearce and Potter [30], [31] provided explicit formulae to compute the factorial moments of the distribution of the number of busy channels on an infinite trunk offered the overflow of a $GI/M/N/N$ queue. Although in principle this distribution can be characterized exactly, in practice, numerical methods must resort to matching its first few moments to a specific renewal process (e.g. [32]).

Simpler moment matching techniques arose much earlier. Wilkinson [33] characterized the overflow stream of the nth alternate trunk in terms of its variance-to-mean ratio, which is denoted with Z and typically referred to as *peakedness*. This represents a two-moment match. (Note that $Z = 1$ for a Poisson stream.) To estimate the blocking probability perceived by a stream characterized by (M, Z) that is offered to a trunk comprising N channels, Wilkinson suggested to consider this stream to be the overflow stream of a fictitious trunk comprising x channels that is offered a Poisson stream of intensity a. Then upon calculating the so-called equivalent random parameters (a, x), as prescribed by Jagerman [34], the blocking probability perceived by the stream characterized by (M, Z) is estimated by $E(a, x+N)/E(a, x)$. This is referred to as the equivalent random method or Wilkinsons method. Fredericks [35] suggested a similar two-moment match based on the notion of peakedness.

Kuczura and Bajaj [36] studied an important generalization of the basic model in which multiple heterogenous streams are offered to a common trunk. A combined stream (M, Z) of mean $M = \sum_i m_i$, variance $V = \sum_i v_i$ and peakedness $Z = V/M$ is used to characterize the presence of each overflow stream (m_i, v_i). Then either the method of [33] or of [35] can be used to calculate the blocking probability, say p, perceived by the combined stream. Hence, the mean of the distribution of the number of busy channels on an infinite trunk offered the overflow of this combined stream is Mp. Accurately apportioning Mp to each marginal stream (m_i, v_i) is a formidable problem plaguing all of these approximations. The only choice is to resort to one of many empirical formulas [37].

Unlike the case in old telephone network of the 50s and 60s where overflows of calls had been hierarchical, namely, calls that overflow from a given tier in the hierarchy overflow to a higher tier. In such a case, the moment matching approaches, such as in [33], [35], can lead to accurate approximations [38] because the dependencies are unidirectional, namely, congestion in a lower tier affects loading of higher tier but not vice versa. However, we consider here a non-hierarchical network [37], where increasing overflow from trunk j may increase the load on trunk k which, in turn, may increase overflow from trunk k to j, etc. This effect is called *mutual overflow* (see page 183 of [37]). It increases the dependencies between the loading in the different service groups which makes it harder to obtain accurate approximations for blocking probability.

A classical approach for evaluation of blocking probability in such networks is the well-known Erlang fixed-point approximation (EFPA). This approximation was conceived by Cooper and Katz [4] in 1964 for the analysis of circuit switched telephony networks. It is based on a one-moment match, whereby each overflow stream is characterized solely in terms of its mean, m_i (i.e. the mean number of busy channels if the stream were to be offered to an infinite trunk). All streams offered to a common trunk comprising N channels are pooled together to form a combined stream that offers an intensity of $\sum m_i$. Traditionally, the blocking probability perceived by the combined stream as well as each marginal stream i is approximated by $E\big(\sum m_i, N\big)$. The overflow of each marginal stream i then goes on to offer an intensity of $m_i E\big(\sum_i m_i, N\big)$ to the next alternate trunk.

In this paper we consider an alternative approximation, in addition to EFPA, for the calculation of end-to-end blocking probabilities in OBS networks. The approximation we consider is our recently introduced Overflow Priority Classification Approximation (OPCA) which was first presented in [10], further explained, analyzed and motivated in [11], and applied to blocking probability estimation for circuit-switched trunk reservation networks in [12]. This approximation represents a radically new approach to the analysis of overflow loss networks, in that traditional moment matching techniques play no role. High level description of OPCA will be provided in IV-A, before the details of the application to OBS networks with deflections is described.

The contributions of this paper are threefold:

- We apply OPCA to analysis of OBS networks with deflection routing employing wavelength reservation. Note that wavelength reservation is analogous to trunk reservation [39] in circuit switched networks and offers protection against the potential instability resulting from excessive deflection routing. See [23] for details.
- We quantitatively evaluate the performance of OPCA and EFPA with respect to OBS over a range of network topologies including fully meshed networks, ring and NSF backbone network, over a range of scenarios of involving different mean values and distributions of burst size. We observe that the maximum value of these methods, namely, max(EFPA,OPCA), is a robust, conservative and accurate blocking probability estimator in most cases.
- We quantify the extent to which deflection routing can enhance the blocking performance and utilization of OBS networks. In this way, we provide a more accurate and scalable approximation to calculate end-to-end blocking probabilities in an OBS network utilizing deflection routing.

The study of OBS networks with deflection routing (which can be viewed as a non-hierarchical overflow network) has been of great interest to many researchers in recent years (see, e.g., [8], [13]–[19], [21]–[23]). Most of these publications study performance by simulations or provide a single node analysis. Zalesky *et al.* [22], [23] used EFPA to evaluate blocking probability in such networks. Here we enhance the accuracy and robustness of the blocking probability evaluation using max(EFPA,OPCA).

III. The Model

In this section we describe the network model. We first outline the network structure that we consider and this is followed by a description of the burst switching algorithms used in the network. Finally, we describe how trunk reservation is implemented in the network model.

A. Network Structure

We consider 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. Therefore, a trunk carries $C_j = f_j w_j$ wavelength channels called *links*.

Each unique pair of origin and destination nodes form a directional origin-destination (OD) pair, m. The set of all OD pairs in the network is denoted $\beta = \{1, 2, \ldots, N(N-1)\}$. We consider directional OD pairs, so $\{i, j\} \in \beta$ represents an OD pair with $i \in \alpha$ being the origin and $j \in \alpha$ the destination, then $\{j, i\}$ and $\{i, j\}$ are two different elements in β. The traffic demand ρ_m of each OD pair $m = \{i, j\} \in \beta$ is composed of bursts transmitted from i to j that follow a Poisson process with parameter ρ_m. The burst lengths are exponentially distributed with unit mean. We note the well-known result that the blocking probability of an M/M/k/k system, known as Erlang B formula, is dependent only on the mean of the service time and it is insensitive to higher moments of the service time distribution. In other words, Erlang B formula applies to the more general model known as M/G/k/k [40]–[43]. This important result has been proven by many authors during the last century [41], [43]–[47]. This indicates that the end-to-end results may also not be too sensitive to the distribution of the burst lengths and will mainly depend on their mean. This will be numerically tested in Section V-H.

Let us consider a directional pair of nodes (i, j), where $i, j \in \alpha$. This pair of nodes is not necessarily an OD pair and both i and j can be intermediate nodes in a route between two origin and destination nodes. Let $U(i, j)$ be the set of routes from node i to node j. The k route between i and j is denoted $U_k(i, j)$, so $U_k(i, j) \in U(i, j)$

In networks where a given pair of nodes has more than one route (i.e. $|U(i, j)| > 1$), the route with the least number of hops is referred to as the primary route denoted $U_0(i, j)$. All the other possible routes from i to j are referred to as alternate routes.

B. Burst Forwarding

At source node i, all bursts with destination node j are transmitted on the first trunk of the primary route $U_0(i, j)$. At each intermediate node, the burst is forwarded on the next trunk in primary route $U_0(i, j)$ until it reaches destination node j. If at any node, including the source node, all the links on the trunk of the route are unavailable, the burst is deflected onto an alternate route. If the burst is deflected at node l, then the set of alternate routes is $U(l, j) - U_0(l, j)$. Preference is given to shorter routes followed by pre-assigned ordering. A given burst is permitted to be deflected at most D times. A burst is considered blocked (discarded/lost) if it arrives at a given node where all output trunks are busy or while trying alternate trunks, the burst reaches the maximum allowable number of deflections.

In our model we assume an ideal case with no guard bands between bursts. In addition, we do not consider specific OBS reservation protocols [48], scheduling algorithms [49], or partial wavelength conversion [50]. Finally, we note that 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 [51].

C. Wavelength Reservation

In a network with wavelength channel reservation, some of the capacity on each trunk is reserved for bursts that have not been deflected [23]. Bursts belonging to OD pair m, on the primary route between OD pair m, are undeflected bursts. In our network model, we set wavelength channel reservation threshold $T_j \leq C_j$ on each trunk j. If the number of links occupied on trunk j is greater than or equal to T_j, only undeflected bursts are permitted to use that trunk.

IV. Blocking Probability Estimation Techniques

In this section we present the techniques we use to estimate blocking probability. The first two are adaptations of EFPA and OPCA to the case of OBS networks with deflections.

TABLE I
LIST OF NOTATION

$a_j^k(m)$	offered load of OD pair m, with k deflections, on trunk j
a_j^k	offered load, with k deflections, on trunk j
$\tilde{a}_j^k$	offered load, up to k deflections, on trunk j
b_j^k	blocking probability of link j for traffic with k deflections
$q_j(i)$	probability of state i for link j (EFPA)
$p_j^k(i)$	probability of state i for link j, with k deflections (OPCA)

Then we provide a qualitative discussion that provides insight into the accuracy of these two approaches under various traffic conditions. Finally, we introduce a method based on the maximum of the blocking probability evaluations of EFPA and OPCA and argue that it can provide an accurate and almost always conservative blocking probability evaluation.

A. EFPA and OPCA

Here we describe the algorithms that adapt EFPA and OPCA to the evaluation of blocking probability in OBS networks with deflection routing. Both algorithms have three steps. The first and the third are common to both EFPA and OPCA. Only Step 2 is different for the two algorithms. To save space we will not repeat Step 1 and 3, and only in Step 2 we will separate the discussion of the two algorithms.

1) Step 1: Offered Loads: As before, the traffic demand, or offered load, of each OD pair m is 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 $j \in \mathcal{J}$. Let b_j^k be the probability that a burst with k deflections is blocked on trunk j. 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. Therefore, the offered load of OD pair m on the second trunk i_2 of the primary route is

$$a_{i_2}^0(m) = \rho_m(1 - b_{i_1}^0). \tag{1}$$

On the other hand, due to congestion, bursts are occasionally blocked on a trunk of the primary route and are deflected onto alternate trunks and routes. The load offered to the first trunk l_1 of the first choice alternative route is related to the load offered to trunk i on the primary route by

$$a_{l_1}^{k+1}(m) = a_i^k(m) b_i^k, \tag{2}$$

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

$$a_{l_2}^{k+2}(m) = a_{l_1}^{k+1}(m) b_{l_1}^{k+1} = a_i^k(m) b_i^k b_{l_1}^{k+1}. \tag{3}$$

2) Step 2: 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

$$a_j^k = \sum_{m \in \beta} a_j^k(m). \tag{4}$$

In addition, let $\tilde{a}_j^k$ be the offered load, with up to and including k deflections, on trunk j. The variables $\tilde{a}_j^k$ and a_j^k are related by

$$\tilde{a}_j^k = \sum_{l=0}^{k} a_j^l(m). \tag{5}$$

EFPA

We evaluate 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) using

$$q_j(i) = \left(a_j^0 + \mathbf{1}\{T_j > i-1\} \sum_{n=1}^{D} a_j^n \right) q_j(i-1)/i, \tag{6}$$

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.

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

$$b_j^k = \begin{cases} q_j(C_j), & k = 0 \\ \sum_{i=T_j}^{C_j} q_j(i), & k \geq 1 \end{cases}. \tag{7}$$

Equations (1) – (7) form a set of fixed-point equations which can be solved by successive substitutions using an algorithm similar to the one used in [23].

OPCA

OPCA is fundamentally different from EFPA. It is able to capture dependency between traffic on different trunks, but it still decouples between trunks to achieve a scalable approximation. It works by using a surrogate second system and estimating the blocking probability in the second system by EFPA. Although the surrogate system may be different from the real system we aim to analyze, the application of EFPA to the surrogate system will provide a better blocking probability approximation for the original problem than application of EFPA to the original problem. The surrogate system is defined by regarding an overflow loss network as if it were operating under a preemptive priority regime where each call is classified according to the number of times it has overflowed and *junior bursts* (bursts that experienced less overflows) are given priority. By giving priority to junior bursts, the seniors bursts that have more "memory" about busy trunks, namely, trunks where all links are busy, are preempted and overflowed and these senior bursts will only attempt trunks which they did not visit before. This way, during a period of congestion, these senior bursts are likely to run out of trunks to visit and they will be blocked and cleared from the system when they reach they maximum allowable number of deflections. During light traffic periods, following after an occasional preemption, the deflected senior burst is likely to have many choices of trunks to attempt and is not likely to be blocked. In this way, OPCA captures trunk load dependencies as in the real system. This is fundamentally different from EFPA that ignores trunk dependencies and treat each trunk as loaded with the same Poisson traffic regardless of loading of other trunks.

Because under OPCA, "junior" bursts are given priority, the priority of a burst is incrementally reduced on each occasion

it overflows. We remind the reader that this prioritization is artificially introduced in the surrogate system to obtain a more accurate approximation and it is not a feature of the real network. A comprehensive set of rigorous and intuitive arguments as well as numerical results were presented in [11], [12] to explain and demonstrate the benefit of OPCA over EFPA.

We evaluate the link state probability $p_j^k(i)$ for each trunk $j \in \mathcal{J}$, for $k \in \{0, \ldots, D\}$ deflections and each state $i \in \{1, \ldots, C_j\}$ using

$$p_j^k(i) = \left(a_j^0 + \mathbf{1}\left\{T_j > i-1\right\} \sum_{n=1}^{k} a_j^n \right) p_j^k(i-1)/i, \quad (8)$$

where $p_j^k(0)$ is set such that $\sum_{i=0}^{C_j} p_j^k(i) = 1$ is satisfied.

The average blocking probability $\bar{b}_j^k$ on trunk $j \in \mathcal{J}$, for bursts with up to and including $k \in \{1, \ldots, D\}$ deflections, is estimated by

$$\bar{b}_j^k = \frac{\sum_{n=0}^{k} \left(a_j^n \sum_{i=T_j}^{C_j} p_j^k(i) \right)}{\tilde{a}_j^k} \quad (9)$$

and $\bar{b}_j^0$ is estimated using the Erlang-B formula, i.e. $\bar{b}_j^0 = E\left(a_j^0, C_j\right)$. The blocking probability, for bursts with $k \in \{0, \ldots, D\}$ deflections, on trunk j is estimated by

$$b_j^k = \begin{cases} \bar{b}_j^0, & k = 0 \\ \frac{\bar{b}_j^k \tilde{a}_j^k - \bar{b}_j^{k-1} \tilde{a}_j^{k-1}}{a_j^k}, & 1 \le k \le D \end{cases}. \quad (10)$$

Note that the blocking probability of undeflected bursts is calculated using the Erlang-B formula.

To obtain the OPCA blocking probability estimates, we start with the primary traffic, i.e., $k = 0$. Then, we solve the fixed-point equations described by (1), (4) and (8), by successive substitutions, to obtain the $p_j^0(i)$ values for $j \in \mathcal{J}$ and $i \in \{1, \ldots, C_j\}$, as well as the values a_j^0 for $j \in \mathcal{J}$ and $\bar{b}_j^0 = b_j^0 = E\left(a_j^0, C_j\right)$.

Next, having all the parameters related to the primary traffic ($k = 0$), we progress to compute the parameters associated with the first deflection traffic ($k = 1$). We solve the fixed-point equations (2), (3), (4) and (8) to obtain the $p_j^1(i)$ values for $j \in \mathcal{J}$ and $i \in \{1, \ldots, C_j\}$, as well as the values a_j^1 for $j \in \mathcal{J}$, and $\bar{b}_j^1$ and b_j^1 using equations (9) and (10), respectively, for every $j \in \mathcal{J}$, where $\tilde{a}_j^1$ is given by (5).

Then, having all the parameters related to the primary and the first deflection traffic ($k = 0$ and $k = 1$), we compute the parameters associated with the second deflection traffic ($k = 2$).

The process of deriving the parameters for $k = 2$ repeats itself until we have all the parameter values for all $k \in \{1, \ldots, D\}$.

3) Step 3: 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

$$P_m = 1 - \frac{\sum_{j \in \mathcal{E}_m} \sum_{k=0}^{D} a_j^k(m)(1 - b_j^k)}{\rho_m}, \quad (11)$$

where $a_j^k(m)(1 - b_j^k)$ is the carried load of OD pair m, with k deflections, on trunk j.

The average blocking probability for the network P is estimated by

$$P = \frac{\sum_{m \in \beta} \rho_m P_m}{\sum_{m \in \beta} \rho_m}. \quad (12)$$

B. EFPA versus OPCA for different traffic regions

In low traffic region, OPCA is accurate and EFPA underestimates the blocking probability. As discussed in [11], OPCA captures well the dependency and occurrences of occasional congestion, while EFPA suffers from errors due to the Poisson and independent assumptions.

By comparison, during a very heavy traffic period, overflow traffic dominates and links are used inefficiently because bursts take longer paths using more links. OPCA considers a surrogate system that gives preemption priority to the primary traffic, so during such heavy traffic load, the primary traffic that use short paths dominates, when in fact the overflow traffic dominates in the real system. Therefore OPCA underestimates the blocking in this very heavy traffic region. On the other hand, EFPA (like the real system) does not give priority to primary traffic, so it can capture the effect of the dominating overflow traffic (longer paths and lower carried load) and therefore it predicts higher blocking probability than OPCA.

Then there is a third intermediate period where the traffic load is in a region between the above two extreme regions. This represents the case where we have sufficiently heavy traffic that in the real system there is a potentially significant drop in the carried traffic while in the EFPA, the fixed-point solution is not unique (see Figures 3 and 5 in [23]). OPCA solution is unique in this intermediate region because it, as discussed, discriminates against overflowed traffic. Henceforth, we call this intermediate region an *unstable* region. The reader is referred to [23] for further discussion on this intermediate unstable region.

C. max(EFPA,OPCA)

The different behaviors of EFPA and OPCA give rise to a new approximation based on choosing the maximal value of the EFPA and OPCA blocking probability approximations designated max(EFPA,OPCA). As demonstrated empirically in Section V, max(EFPA,OPCA) can lead to accurate approximations in most scenarios, and almost always it seems to be a conservative approximation.

V. Numerical Results

The performance of OPCA is evaluated and compared to the performance of EFPA using simulations. We consider ring networks, fully meshed networks and the 13-node National Science Foundation network (NSFNET). The NSFNET is often chosen to represent a core national network, and the ring and fully meshed topologies are two extreme network topologies that are often used as physical or logical topologies. To limit excessive simulation times we focus on traffic loads that result in blocking probabilities above 10^{-5}. In our simulations the burst arrival process for each OD pair follows a Poisson process as in our analytical modelling. Also, as in our analysis routing preference is given to shorter routes followed by pre-assigned ordering. The pre-assigned order is chosen at random before the simulation runs and it remains unchanged. Then the corresponding analytical results are based on the same order.

The difference between the simulation and the analytical modelling is that the simulation does not make the trunk independence assumption. As such, the simulation also does not assume the process of overflowing bursts at each trunk to be Poisson. We do not simulate the intricacies of the burst reservation process (e.g. bursts do not seek to reserve wavelength resources before their arrival, as per the just-enough-time scheme [52]). Instead, we assume a burst seeks a wavelength at the instant it arrives as in the JIT scheme [6]. In this way, the simulation exclusively tests the error introduced by the independence and the Poisson assumptions.

Our simulation also allows for a given burst, assuming it is long enough, to be transmitted simultaneously on multiple consecutive trunks (analyzed in [53] only for the special case of a network composed of optical cross-connects connected in tandem). This phenomenon is not captured by our analytical modelling which assumes decoupling and independence of the various trunks.

A. Fully Meshed Network Topologies

Fig. 1 shows the average blocking probability (P) in a 6-node fully meshed network for average offered loads, ρ_m from 35 to 50 erlangs. Each trunk has 50 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. The wavelength channel reservation threshold is set to 45 for each trunk. The results indicate that OPCA is accurate and conservative for offered loads from 35 to 40. OPCA underestimates the blocking probability when the offered load is greater than 40. On the other hand, EFPA gives accurate and conservative results for offered loads greater than 42, but underestimates the blocking probability when the offered load is less than 42. We observe that for this case, max(EFPA,OPCA) provides the best approximation which is also conservative except for loads between 40 and 42 erlangs.

In Figs. 2 and 3 we consider 8- and 10-node fully meshed networks, respectively, and again compare between OPCA and EFPA. For the 8-node the maximal number of deflections increase to 6, while in the 10-node network it increases to 10. We observe that as the number of nodes and the maximal number of deflections increases, the EFPA approximation tends to overestimate the blocking probability for high loads, and then as in the case of the 6-node network, underestimate in the case of low loads.

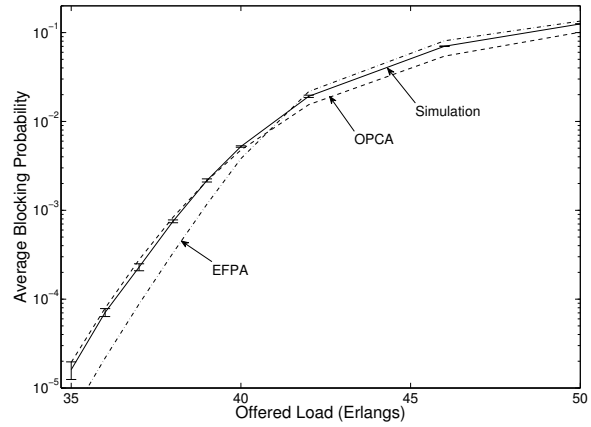

Fig. 1. Blocking probability of OPCA and EFPA vs. simulation results for a 6-node fully meshed topology with 90% reservation threshold, and the number of deflections is limited to 4.

Then in Fig. 4, we consider the 10-node fully meshed topology where the reservation threshold is extended to 80%. Lowering the reservation threshold, provides greater protection for new (undeflected) flows. This suppresses the unstable region, and reduces overflow traffic, which in turn decreases the Poisson and independent errors (which improves accuracy of both EFPA and OPCA). In addition, OPCA gives priority to un-deflected bursts, which is consistent with the effect of an aggressive reservation threshold. This results in higher accuracy of OPCA. As a result, max(EFPA,OPCA) is more accurate than in the case of a 90% reservation threshold.

Notice that in the scenario presented in Fig 3, the max(EFPA,OPCA) loses certain accuracy in the high load range where EFPA over-estimates the blocking probability, but again, it is almost always conservative. As we use blocking probability estimations for dimensioning purposes, the fact that max(EFPA,OPCA) may overestimate the blocking probability for certain very high loads (low performance - and probably unstable) range is not a significant issue because this range must be avoided. Notice that for acceptable blocking probabilities such as 10^{-3} or 10^{-4}, the error introduced by max(EFPA,OPCA) is small in terms of error in dimensioning. Even for the most inaccurate scenario of the 10 node network, if we aim to dimension a network based on say 10^{-3} blocking probability and use the max(EFPA,OPCA) approximation for this purpose, we will only over-dimension the network by some 2% which is an acceptable error especially given the much larger errors in traffic prediction.

B. NSF Network

We consider an NSF network with 13 nodes and 32 trunks. The topology of the NSF network is shown in Fig. 5. As before, each trunk has 50 links and the wavelength channel reservation threshold is set to 45 for each trunk. We randomly select a set of 12 OD pairs and simulate the network for

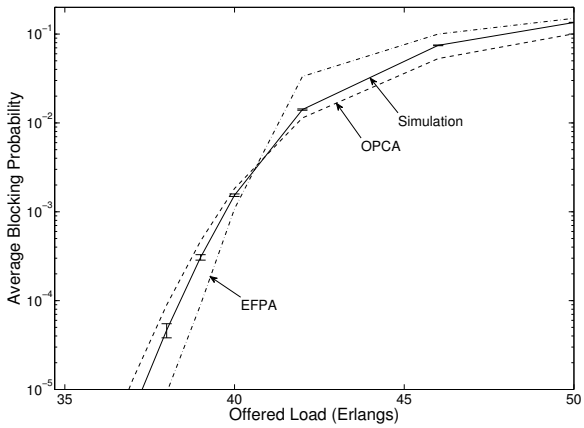

Fig. 2. Blocking probability of OPCA and EFPA vs. simulation results for a 8-node fully meshed topology with 90% reservation threshold, and the number os deflections is limited to 6.

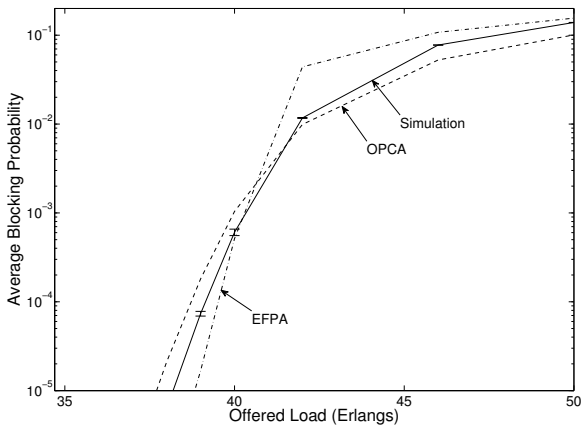

Fig. 3. Blocking probability of OPCA and EFPA vs. simulation results for a 10-node fully meshed topology with 90% reservation threshold, and the number of deflection is limited to 8.

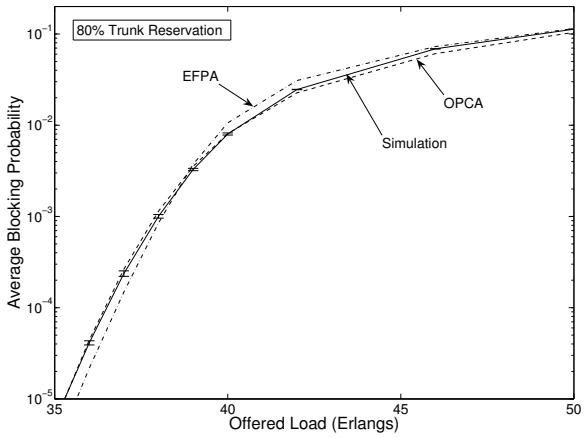

Fig. 4. Blocking probability of OPCA and EFPA vs. simulation results for a 10-node fully meshed topology with 80% reservation threshold, and the number of deflection is limited to 8.

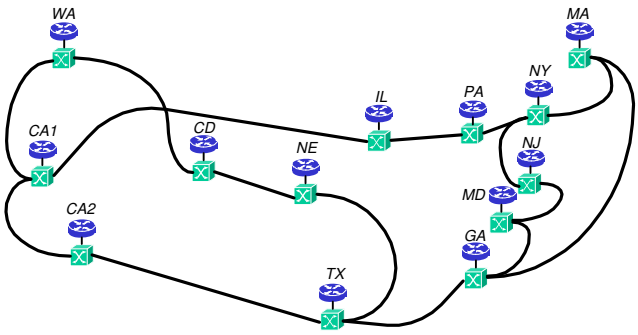

Fig. 5. NSF network topology, each solid line represents two uni-directional trucks in opposing directions.

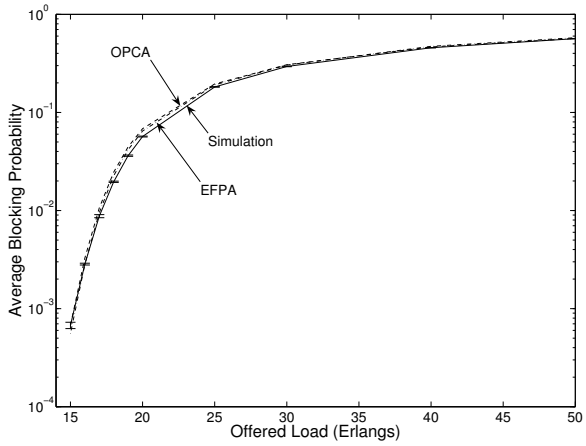

Fig. 6. Blocking probability comparison of OPCA vs. EFPA for NSF topology with 90% reservation threshold. The OD pairs are according to Set 1 in Table II.

average offered loads, ρ_m from 15 to 50 erlangs. Figs. 6 and 7 show the average blocking probability of the network, obtained using simulations, when the sets of OD pairs are according to Set I and Set II, respectively from Table II. We also present in these two figures the corresponding blocking probability estimates using OPCA and EFPA. The blocking probability estimated using OPCA is very close to that obtained using EFPA. In addition, the simulation results indicate that the blocking probability estimates obtained using either OPCA or EFPA are accurate. Thus max(EFPA,OPCA) is also accurate.

These results demonstrate that max(EFPA,OPCA) does not improve significantly the already accurate results of EFPA in networks that are not heavily meshed. Nevertheless, it is important to have available a method which is robust and is not dependent on topology. Based on all the results we present, max(EFPA, OPCA) satisfies this requirement.

C. 6-Node Ring Network

Fig. 8 shows the average blocking probability in a 6-node bi-directional ring network for average offered loads, ρ_m, varied between 7 and 10 erlangs. Each trunk has 50 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. As with the 6-node fully meshed and NSF networks, the wavelength

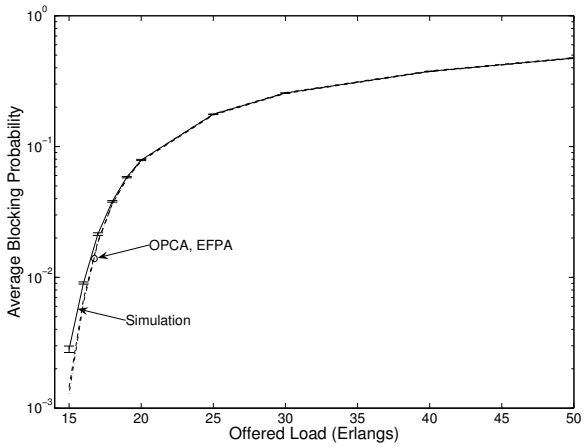

Fig. 7. Blocking probability comparison of OPCA vs. EFPA for NSF topology with 90% reservation threshold. The OD pairs are according to Set 2 in Table II.

TABLE II

TWO SETS OF INGRESS AND EGRESS ROUTER PAIRS

Set 1		Set 2	
Ingress	Egress	Ingress	Egress
WA	MD	NJ	NE
CA1	IL	IL	NY
CA1	MA	CA2	WA
CA2	MA	WA	PA
TX	NY	CA2	TX
GA	MA	CA2	PA
MD	WA	CA1	GA
IL	CA1	MD	NJ
MA	CA1	MA	PA
MA	CA2	CA2	CA1
NY	TX	NE	GA
MA	GA	PA	CD

channel reservation threshold is set to 45 for each trunk. The blocking probability estimated using OPCA is very close to that obtained using EFPA. In addition, as is the case for the NSF Network, the simulation results indicate that the blocking probability estimates obtained using either OPCA or EFPA are accurate.

D. Blocking Versus Number of Deflections and Trunk Size

We present here results for the blocking probability over a range of values for the maximal allowable number of deflections and the trunk size (namely, the number of links per trunk). The aims are to study the effects of the allowable number of deflections and trunk size on blocking probability and to evaluate the accuracy of our max(EFPA,OPCA) approximation. To evaluate the accuracy of max(EFPA,OPCA) against the number of deflections allowed and trunk size, we focus on a fully meshed network because the low average nodal degree in ring networks and the NSF network restricts the alternate paths and therefore the number of deflections [25]. We consider a reservation threshold of 90% and vary the maximal allowable number of deflections between 0 – 6. For trunk size values, we consider 10, 50 and 100 links per trunk.

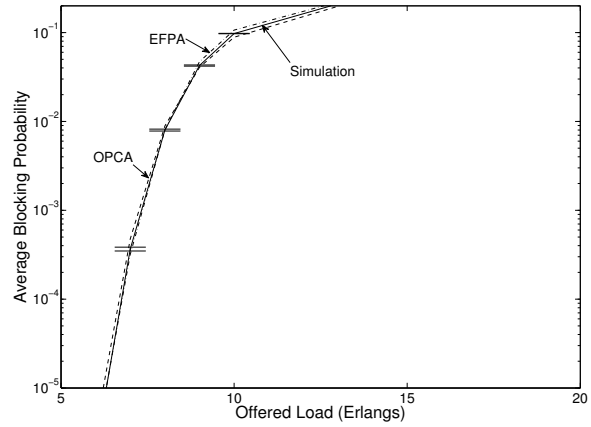

Fig. 8. Blocking probability comparison of OPCA vs. EFPA for a 6-node ring topology with 90% reservation threshold.

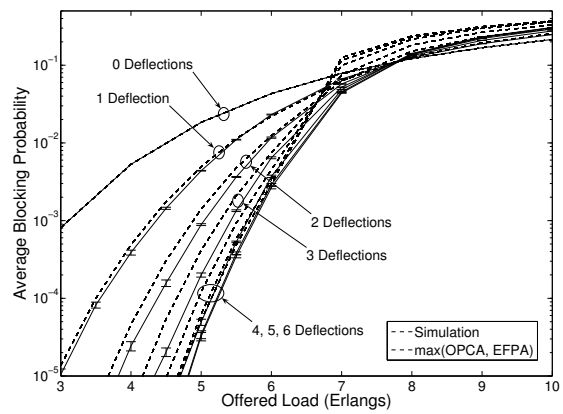

Fig. 9. Blocking probability evaluations based on simulations and max(EFPA, OPCA) estimates for a 6-node fully meshed network with maximal allowable number of deflections ranges between 0 – 6. Each trunk in the network has 10 links with a reservation threshold of 90%.

In Figures 9, 10, and 11, we present results for the blocking probability evaluations based on simulations and max(EFPA, OPCA) estimates for the cases where the numbers of links per each trunk in the network has 10, 50 and 100 links respectively. The 95% confidence intervals based Student's t-distribution are also provided for the simulation results. We can see that the max(EFPA, OPCA) estimates the simulation results reasonably well, although in many cases the estimates fall outside the confidence intervals. We also observe reduction in marginal benefit as the number of allowable deflections increases. There is a clear benefit, in our example to increase the maximal number of deflection all the way to four. However, increasing this number to five or six, does not significantly reduce the blocking probability.

E. Utilization

An important measure to a designer is resource utilization. We target blocking probability of 10^{-3} and aim to find the maximal achievable utilization such that the blocking

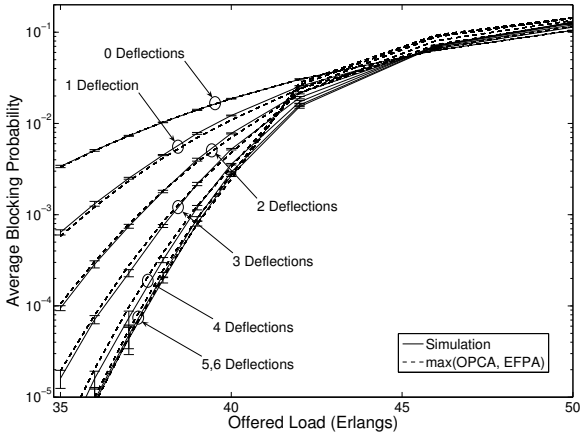

Fig. 10. Blocking probability evaluations based on simulations and max(EFPA, OPCA) estimates for a 6-node fully meshed network with maximal deflections between 0 – 6. Each trunk in the network has 50 links with a reservation threshold of 90%.

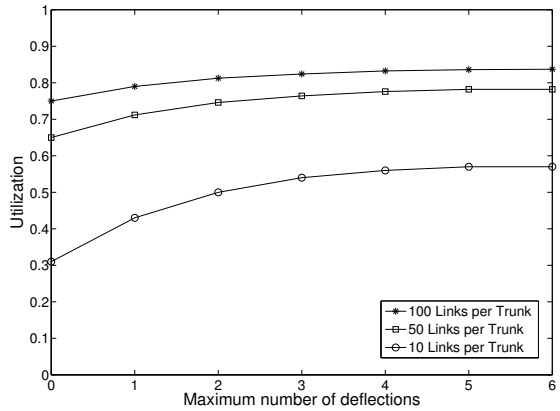

Fig. 12. The utilization of a 6-node fully meshed network with reservation threshold of 90%, target blocking probability of 10^{-3} and maximal deflections between 0 – 6 when the number of links per trunk is 10, 50 and 100.

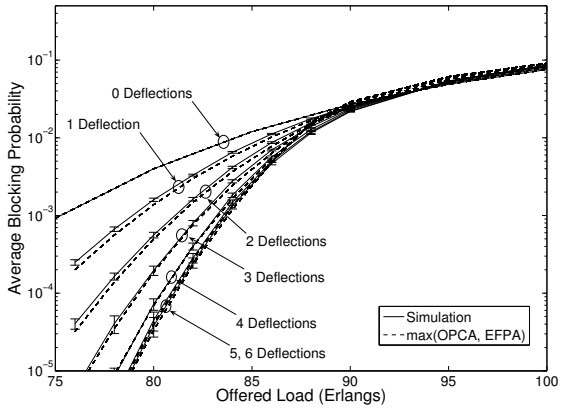

Fig. 11. Blocking probability evaluations based on simulations and max(EFPA, OPCA) estimates for a 6-node fully meshed network with maximal deflections between 0 – 6. Each trunk in the network has 100 links with a reservation threshold of 90%.

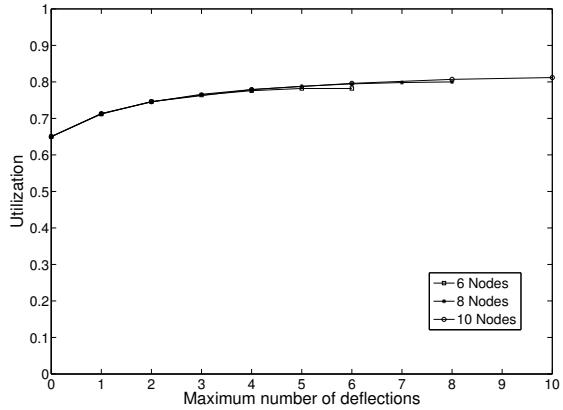

Fig. 13. The utilization of a 6, 8 and 10-node fully meshed networks with 50 links per trunk and reservation threshold of 90%, target blocking probability of 10^{-3} and maximal deflections between 0 – 6, 0 – 8 and 0 – 10 for the 6, 8 and 10-node networks, respectively.

probability will not exceed 10^{-3}. In Fig. 12, we provide a plot of the simulated average blocking probability (using the results of the previous figures) against offered load for 0 – 6 maximal deflections. The results show that increasing the number of deflections can provide significant utilization gain in fully meshed OBS networks. This is especially true for the cases where the number of links per trunk is low, where only low utilization is achievable in the case of no deflections. We also observe again the reduction in marginal benefit. Clearly, beyond four deflections the additional utilization gain for the present case is minor.

Next, we investigate if the above results on utilization achieved for a 6-node network are applicable if the size of the network increases. In Fig. 13 we present utilization results (again, based on simulated average blocking probability using the results of the previous figures) also for an 8-node and 10-node fully meshed networks, 50 links per trunk and 90% utilization, and again targeting 10^{-3}. We observe that in the example presented, the network size does not significantly affect the utilization results.

F. Threshold

We have already demonstrated that having lower threshold (more protection for undeflected bursts) leads to better accuracy of max(EFPA,OPCA). We now further examine the effect of threshold level on the accuracy of max(EFPA,OPCA).

In Fig. 14, we consider a fully meshed network with six nodes and 50 links per trunk and vary the traffic load and the threshold level. We observe that for the case of 80% reservation threshold, represented by the curves denoted 40, the accuracy of max(EFPA,OPCA) is excellent. Fairly good accuracy is achieved in the case denoted 45 where we have 90% reservation threshold. However, in the case denoted 48 where we have 96% reservation threshold (almost no

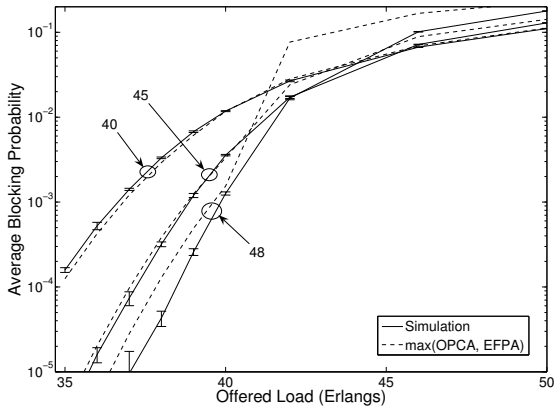

Fig. 14. Blocking probability comparison of max(OPCA,EFPA) versus simulation results for a 6-node fully meshed topology with 80% (denoted 40), 90% (denoted 45) and 96% (denoted 48) reservation thresholds.

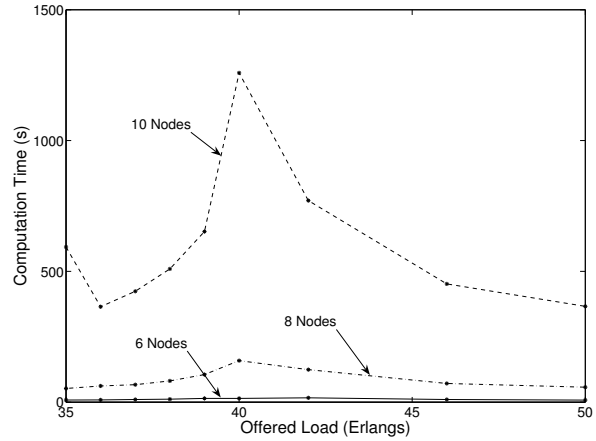

Fig. 15. Running times of EFPA for a 6-node, 8-node and 10-node fully meshed topology with 90% reservation threshold. The maximal number of deflections is 4, 6 and 8 for the 6, 8, and 10 node networks, respectively.

reservation), the accuracy of the estimate falls and this is because the network itself becomes unstable due to deflections.

G. Running Time

Both EFPA and OPCA are based on fixed-point solutions. Because it is difficult to evaluate analytically their convergence rate, we rely on empirical measurements to evaluate and compare their running time. In the examples studied, OPCA has been faster than EFPA as demonstrated in Figs. 15, 16 and 17. Figs. 15 and 16 represent absolute running times while Fig. 17 illustrates the ratios of running times OPCA/EFPA.

From the empirical evidence, the running time of OPCA is clearly no longer than that of EFPA. This implies that the running time of max(EFPA,OPCA) is not longer than twice that of EFPA. Given that EFPA is known to be scalable, max(EFPA,OPCA) will also be scalable.

The behavior of the convergence of EFPA (which also applies to OPCA) is interesting. We will attempt to provide an intuitive explanation for this behavior. It seems that there are two main factors at play that affect the speed of convergence. One factor is the level of traffic (and its effect on the proportion of overflow traffic) and the other is the sensitivity of the EFPA blocking probability to the load. Consider the 80% traffic load (40 erlangs) scenario presented in Fig. 3. Notice also the very steep gradient in the region. In such a case, significant error in end-to-end blocking probability prediction possibly implies also significant errors in link blocking probability. This leads, in turn to a significant error in overflow predictions which again cause errors in end-to-end blocking probability which slows down the convergence. On the other, consider for example the heavy traffic scenario represented by the region around 48 erlangs in Fig. 3. In this case, the end-to-end blocking probability is not sensitive to changes in the load and errors in blocking lead to less significant errors in overflow traffic which lead to faster convergence than the previous 40 erlangs scenario. Now consider the 39 erlangs scenario in Fig. 3, where the gradient is at least as steep as in the 40 erlangs scenario. However, in this case, since we have lighter traffic and the overflow load is far less significant (notice the drop in blocking probability by two order of magnitudes in the 39 erlangs relative to the 40 erlangs case), errors in prediction of the overflow will not lead to significant errors in total offered load to the links and therefore we may expect faster convergence than in the 40 erlangs case. Traffic lighter than 39 erlangs where the blocking probability is very small may lead to unexpected behavior of running time due to numerical computation difficulties.

The above is consistent with the peak observed in running time in Fig. 15 at 40 erlangs for the 10-node case. Notice also the less steep gradient in Fig. 2 and much less in Fig. 1 which explains the lower peak for the 8-node case and the almost no peak for the 6-node case. The results presented for OPCA in Fig. 16 around 40 erlangs for the 10-node case are high but not as high as the peak of EFPA presented in Fig. 15. This is consistent with our explanation. Observe that in Fig. 3, the OPCA gradient at 40 is not as steep at that of EFPA.

H. Sensitivity to burst length

Here we examine the sensitivity of max(EFPA,OPCA) to burst length. First, we fix the mean of the burst size and examine the sensitivity of max(EFPA,OPCA) to higher moments (shape of the distribution) by considering burst length distributions other than exponential, as the exponential distribution assumed by max(EFPA,OPCA) may not be the right one to characterize the burst size. Then, we vary the burst mean, maintaining the exponential distribution, to examine the accuracy of max(EFPA,OPCA) for a wide range of mean burst lengths. This will validate the applicability of max(EFPA,OPCA) to OPS and OBS. Furthermore, as mentioned above, long bursts may be served by several trunks simultaneously - an effect which is not considered by max(EFPA,OPCA), so it is important to know the error this introduces.

For both examinations, we consider a 6-node fully meshed

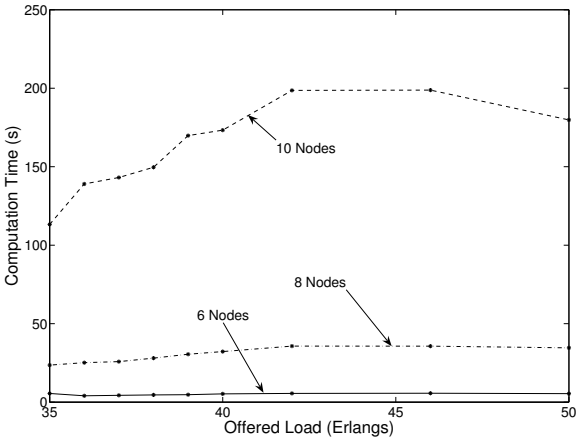

Fig. 16. Running times of OPC for a 6-node, 8-node and 10-node fully meshed topology with 90% reservation threshold. The maximal number of deflections is 4, 6 and 8 for the 6, 8, and 10 node networks, respectively.

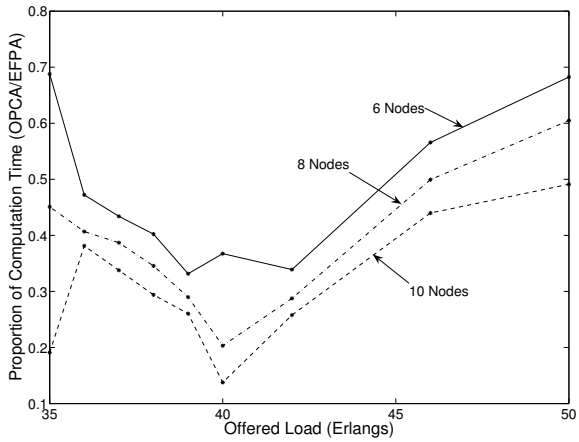

Fig. 17. Ratios of running times OPCA/EFPA for a 6-node, 8-node and 10-node fully meshed topology with 90% reservation threshold. The maximal number of deflections is 4, 6 and 8 for the 6, 8, and 10 node networks, respectively. A value of 0.5 means that OPCA took half the time.

network with 50 links per trunk with 90% reservation threshold. The number of deflections is limited to 4.

1) Sensitivity to shape of the burst size distribution: To study the sensitivity of max(EFPA,OPCA) to higher moments of the burst size distribution we consider the following four scenarios. In the first scenario the burst length is exponentially distributed with mean 1. In the second scenario, we maintain the mean burst size the same as in the first scenario (equal to 1), but we increase its variance. In particular, we consider the case that the burst length is hyper exponentially distributed. In particular, with probability 1/6 it is exponentially distributed with mean 5, and with probability 5/6 it is exponentially distributed with mean 1/5. In the third scenario, we further increase the variance of the burst length but maintain its mean of 1. We consider the burst length to be hyper exponential distributed: with probability 1/11 it is exponentially distributed with mean 10, and with probability 10/11 it is exponentially distributed with mean 1/10. In the fourth scenario, we consider a heavy tail distribution for the burst-size maintaining its mean at 1, but with infinite variance. In particular, we consider the burst size B to follow a Pareto distribution with a complementary distribution function (CDF) that takes the form:

$$\mathrm{Prob}\left(B > x\right) = \begin{cases} \left(\frac{\delta}{x}\right)^{\gamma}, & x \geq \delta, \\ 1, & \text{otherwise}, \end{cases} \tag{13}$$

where $\delta > 0$ [seconds] is the scale parameter (minimum burst size) and $\gamma > 0$ is the shape parameter of the Pareto distribution. The mean of B is given by

$$\mathrm{E}\left(B\right) = \begin{cases} \infty, & 0 < \gamma \leq 1, \\ \frac{\delta\gamma}{\gamma-1}, & \gamma > 1. \end{cases} \tag{14}$$

For $0 < \gamma \leq 2$, the variance $\mathrm{Var}(B) = \infty$. In our simulation we set $\delta = 0.5$ and $\gamma = 2$.

Simulation results for the blocking probability are presented in Fig. 18. In these simulation results, the horizontal axis represents the actual (not theoretical) traffic load observed during the simulation. Such presentation of results is important when heavy tailed random deviates are generated because there can be significant difference between the expected and the measured traffic load. We observe that the blocking probability results for the first three scenarios are indistinguishable when plotted - demonstrating very weak sensitivity to the second and higher moments of burst length distribution. The fourth scenario related to heavy tailed bursts gives a slightly different blocking probability curve, but still very close to the results of the other three scenarios. This is consistent with the bufferless nature of the network we consider. This is also consistent with the above mentioned result related to the M/M/k/k system which is known to give blocking probabilities which are insensitive to the form of the burst length distribution and only depends on its mean. This also indicates that the accuracy of max(EFPA,OPCA) does not depend significantly on the form of the burst length distribution.

2) Sensitivity to the mean burst size: To study the sensitivity of max(EFPA,OPCA) to the mean burst size, we consider five cases where the mean burst size is equal to 0.1, 1, 10, 100 and 1000. Notice that all other previous results presented above the mean is equal to 1. Simulation results and max(EFPA,OPCA) approximations for the blocking probabilities in the five cases are presented in Fig. 19. As expected, in the interesting range where the blocking probability is between 10^{-3}, and 10^{-4}, max(EFPA,OPCA) underestimate somewhat the blocking probability in the case of larger bursts, probably due to dependency between loads on consecutive trunks created by long bursts which is not considered by max(EFPA,OPCA). Nevertheless, the error in dimensioning, namely, the difference in traffic load between the simulation results and max(EFPA,OPCA) in the case of 10^{-3} blocking probability, for the large bursts scenarios, i.e., mean burst = 100 or 1000, is no more that 2%.

VI. Conclusion

We have demonstrated that max(EFPA,OPCA) is a reasonably accurate approach to approximate blocking probability

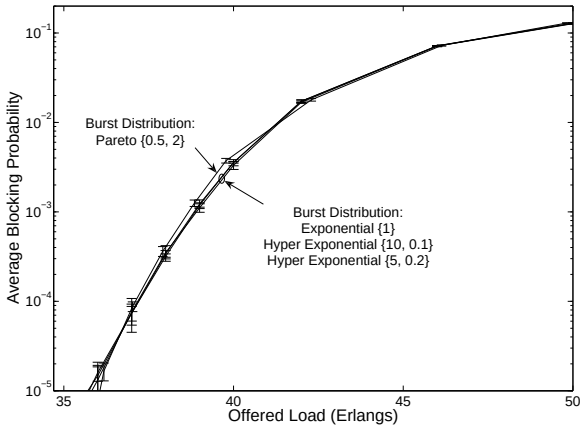

Fig. 18. Blocking probability versus traffic load for four different burst size distributions for a 6-node, fully meshed network with 90% reservation threshold. Number of deflections limited to 4.

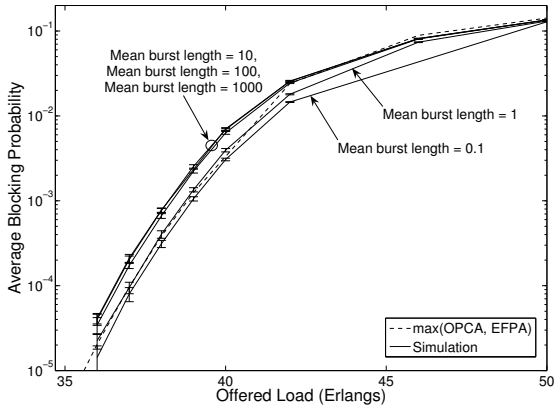

Fig. 19. Blocking probability versus traffic load for four different burst size means for a 6-node, fully meshed network with 90% reservation threshold. Number of deflections limited to 4.

of OBS and OPS networks using deflection routing with sufficient protection to avoid instability. Although in some cases max(EFPA,OPCA) is not perfectly accurate, especially in the load region within the gap between the high and low traffic load, max(EFPA,OPCA) is clearly an improvement over EFPA and almost always conservative. We have demonstrated that even for the most inaccurate scenario, if we aim to dimension a network using the max(EFPA,OPCA) approximation, we will only over-dimension the network by some 2% which is an acceptable error. We have further demonstrated that the results are not sensitive to the shape of burst size distribution and that for large bursts max(EFPA,OPCA) may under-estimate required dimensioning by around 2%. By empirical evidence, the running time of max(EFPA,OPCA) is no longer than twice that of EFPA so max(EFPA,OPCA) is computationally efficient and scalable.

We have also demonstrated that in certain topologies where there are many alternative routes, e.g. fully meshed topology, a significant improvement in utilization can be achieved by using multiple deflections. Using our results, we have demonstrated the reduced marginal benefit of increasing the maximal allowable number of deflections and evaluated the achievable utilization as a function of this number.

In topologies where there are not many alternative routes, max(EFPA,OPCA) does not improve significantly the already accurate results of EFPA. Nevertheless, max(EFPA, OPCA) is not less accurate than EFPA in such networks, and since it is robust and applicable to a wider range of topologies, max(EFPA, OPCA) has an overall advantage over EFPA.

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