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Computing Blocking in a Hybrid Optical Switch*

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Abstract: We consider a hybrid optical switch that allows for optical burst switching (OBS) as well as optical circuit switching (OCS). Long-lived flows use OCS, and short-lived flows comprising best-effort traffic use OBS. In this way, OBS allows statistical multiplexing of capacity for best-effort traffic, while OCS is offered as a premium service for traffic demanding high QoS. We use a multidimensional continuous time Markov chain to compute the blocking probability in a hybrid optical switch that is fed by a finite number of on/off sources. We then cosnider a scalable fixed-point approximation to cope with a hybrid optical switch of practical dimensions. The accuracy of our approximation as well as its sensitivity to non-exponentially distributed on and off periods is tested via simulation. Finally, we suggest an approach to dimension capacity for a hybrid optical switch.
Keywords: Hybrid optical switching, optical burst switching (OBS), optical circuit switching (OCS), blocking probability.

1. INTRODUCTION

Three approaches to optical switching have been proposed for wavelength-division multiplexed networks: optical circuit switching (OCS) [8], optical packet switching (OPS) [3,7] and

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optical burst switching (OBS) [15]. Although OPS is ideal in many regards, it is not highly practical because it mandates the use of costly optical technologies such as fiber delay lines to allow optical buffering of a packet while its header is processed. We do not consider OPS in this paper.

OCS encompasses a range of approaches to switching. Two-way reservation is inherent to all forms of OCS. With OCS, traffic is transmitted once it has been confirmed that sufficient wavelength resources are available to set up an all-optical path. OCS has been described prevalently in literature [6,8].

OBS is a highly dynamic approach to switching that is based on one-way reservation. The basic switching entity in OBS is a burst. A burst is train of packets that is transmitted via an all-optical path. Associated with each burst is a header. The key feature distinguishing OBS from OPS is that a burst is separated from its header by an offset time. An offset time eliminates the need to optically buffer a burst during the time required to process its header at each intermediate node. Most of the early literature [14–17,19] describes the workings of OBS in detail as well as recent work [1,2,5], we have therefore only given a brief description.

The choice between OCS and OBS is strongly dependent on the statistical distribution of arriving traffic flows. In particular, long-lived traffic flows are suited to OCS, while sporadic short-lived flows are suited to OBS. OCS is not suited to short-lived flows because the length of a short-lived flow may be several orders of magnitude smaller than the time required to dynamically set up an all-optical path for it and issue an acknowledgment to its sender, as per OCS. However with OBS, an acknowledgement is not issued to its sender, and transmission can therefore begin sooner, resulting in reduced delay and better wavelength utilization. The disadvantage of OBS is that blocking is possible at intermediate nodes.

In this paper, we consider a hybrid optical switch that allows for OCS and OBS. Arriving traffic flows are classified as either long-lived or short-lived. Normally, long-lived flows use OCS, and short-lived flows use OBS. However, it is possible to set up a circuit and use it for many short-lived flows to provide premium service. In this way, OBS allows statistical multiplexing of capacity for best-effort traffic, while OCS is offered as a premium service for traffic demanding high QoS. The rationale behind hybrid optical switching is to maximize network utilization, while satisfying QoS.

Architectures for a hybrid optical switch were recently proposed in [13,20]. In this paper, we evaluate the performance of a hybrid optical switch in terms of blocking probability. We do not discuss the pros and cons of different architectures, but rather focus on computing blocking probability.

Foremost, we use a multidimensional continuous time Markov chain to compute the blocking probability in a hybrid optical switch that is fed by a finite number of on/off sources. We argue that this is not a simple application of the usual Engset system because with OBS, a source essentially becomes ‘frozen’ during the time it is dumping a blocked burst. A frozen source does not generate new arrivals. However, the usual Engset system does not account for the state where a source may be dumping a blocked burst, and thus overestimates blocking of traffic using OBS. Therefore, we consider a modified Engset system where in addition to the usual on and off states (idle and busy), we introduce a new state, which we term the *frozen state* that takes into account frozen sources.

We then consider a scalable fixed-point approximation to cope with a hybrid optical switch of practical dimensions. We prove that our fixed-point approximation converges. Finally, the accuracy of our approximation as well as its sensitivity to non-exponentially distributed on and off periods is tested via simulation.

Throughout this paper we make the following assumptions:

A.1) Zero offset time between a header and its burst. (We make this is assumption to avoid dealing with the unsolved problem of calculating blocking probabilities in a finite server queue where the time at which a customer arrives is separated from the time at which it requests service by different offset times.)

A.2) A burst header offers no load.

A.3) A blocked burst is dumped and never returns.

A.4) A blocked circuit is cleared and never returns.

A.5) For each of a finite number of sources, traffic arrives according to an on/off process, where on periods and off periods are exponentially distributed.

We remark that performance evaluation of hybrid switching in the context of electronic networks has been considered in [4,10,12,22,23].

This paper is an extension of our earlier work in [18]. In [18], in addition to the fixed-point approximation considered in this paper, we considered several other approximations for computing blocking in a hybrid optical switch and considered the case where traffic using OCS is given preemptive priority over traffic using OBS. Preemptive priority ensures that existing levels of service offered to traffic using OCS are maintained as a network is hybridized to allow for OBS. We do not consider preemptive priority in this paper.

The main contributions of this paper are: to further study the sensitivity of our fixed-point approximation and the continuous time Markov chain to non-exponentially distributed on and off periods; and, to further the understanding of dimensioning capacity for a hybrid optical switch.

We will show that our fixed-point approximation and the continuous time Markov chain are mildly sensitive to non-exponentially distributed on and off periods. This suggests that our approximation is valid under traffic scenarios that can be characterized as an on/off (renewal) arrival process.

In particular, for low blocking, it will be evident that the continuous time Markov chain closely resembles an Engset system [9]. An Engset system is known to be insensitive to the distribution of on and off periods [11]. This is intuitively pleasing in the sense that it provides further evidence suggesting that our results are not too sensitive to non-exponentially distributed on and off periods for low blocking. For high blocking, the continuous time Markov chain does not resemble an Engset system because the presence of frozen sources is no longer insignificant.

This paper is organized as follows. In Section 2, we define the continuous time Markov chain used to model a hybrid optical switch, and then consider a scalable fixed-point approximation. Section 3 is devoted to numerical results; in particular, quantifying the accuracy of our fixed-point approximation as well as testing the sensitivity of the continuous time Markov chain and our approximation to non-exponentially distributed on and off periods. Finally, the problem of dimensioning capacity in a hybrid optical switch is considered in Section 4.

2. AN OPTICAL HYBRID SWITCH

We consider an optical hybrid switch fed by M homogenous on/off sources, each of which represents an ingoing wavelength. A source seeks one of K outgoing wavelengths during an on period. We consider the non-trivial case $M > K$. We assume on and off periods are exponentially distributed and sources are independent. A source may generate either a circuit or a burst.

For each source, a period during which packets are transmitted, either via OCS or OBS, is referred to as an on period, and an idle period between two successive on periods is referred to as an off period. Let $1/\mu_b$ and $1/\lambda_b$ be the mean on period and mean off period for bursts. Let $1/\mu_c$ and $1/\lambda_c$ be the mean on period and mean off period for circuits. Furthermore, let $\lambda = \lambda_b + \lambda_c$. Therefore, the probability that a new arrival is a burst is λ_b/λ, and the probability that new arrival is a circuit is λ_c/λ. Typically, $1/\mu_c \gg 1/\mu_b$ and $\lambda_b > \lambda_c$.

Thus far, it seems we have defined an Engset-type loss model with M sources, K servers and two arrival classes. However, using the usual Engset formula [9,11] to compute blocking will overestimate blocking, especially for high loading. This is because according to the usual Engset system, a source that is dumping a burst continues to generate arrivals at rate λ, when in fact such a source does not generate arrivals.

As we alluded to earlier, a source dumping a burst behaves as if it were being served by a dummy server and does not become idle until the entire burst is dumped. We refer to a source that is dumping a burst as a *frozen source*.[3] Note that since OCS is based on two-way reservation, traffic using OCS is not dumped.

2.1. Exact Blocking Probability

At any time instant in steady-state, a source is either idle, frozen, transmitting packets via OCS or transmitting packets via OBS. Let $X_{i,j,k}$ be the state that i sources are transmitting packets via OBS, j sources are transmitting packets via OCS and k sources are frozen. The number of idle sources is then completely specified and is given by $M - i - j - k$. Let $\Lambda = \{X_{i,j,k} | i = 0, \ldots, K; j = 0, \ldots, K; k = 0, \ldots, M - K; i + j \leq K\}$ be the state-space of the underlying continuous time Markov chain, and let $\pi_{i,j,k} = \mathbf{P}(X_{i,j,k} = x)$, $x \in \Lambda$, be its steady-state distribution. Under appropriate conditions a unique distribution exists and can be computed by solving the following system of balance equations. For $i + j < K$,

$$\begin{aligned} & \pi_{i,j,k}\big((i+k)\mu_b + j\mu_c + (M-i-j-k)\lambda\big) \\ = \; & \pi_{i,j,k+1}(k+1)\mu_b + \pi_{i,j-1,k}\big(M-(i+j-1+k)\big)\lambda_c + \pi_{i,j+1,k}(j+1)\mu_c \\ + \; & \pi_{i-1,j,k}\big(M-(i-1+j+k)\big)\lambda_b + \pi_{i+1,j,k}(i+1)\mu_b, \end{aligned} \tag{1}$$

and for $i + j = K$,

$$\begin{aligned} & \pi_{i,j,k}\big((M-K-k)\lambda_b + (k+i)\mu_b + j\mu_c\big) \\ = \; & \pi_{i,j-1,k}(M-K+1-k)\lambda_c + \pi_{i-1,j,k}(M-K+1-k)\lambda_b + \pi_{i,j,k+1}(k+1)\mu_b \\ + \; & \pi_{i,j,k-1}(M-K-k+1)\lambda_b. \end{aligned} \tag{2}$$

In (1) and (2), $\pi_{i,j,k} = \mathbf{P}(X_{i,j,k} = x) = 0$ for $x \notin \Lambda$. Introducing the normalization equation $\sum_{i,j,k} \pi_{i,j,k} = 1$ gives rise to a linearly independent system of equations, which can be solved

[3]The reader is referred to [21] for details on the notion of a frozen source and an example demonstrating the inaccuracy of the standard Engset formula in computing burst blocking.

with elementary methods to compute the distribution $\pi_{i,j,k}$.

The total load offered by OBS and OCS is given by

$$T_o = \sum_{i,j,k} (M - i - j - k)(\lambda_b/\mu_b + \lambda_c/\mu_c)\pi_{i,j,k},$$

and the total load carried by OBS and OCS is given by

$$T_c = \sum_{i,j,k} (i + j)\pi_{i,j,k}.$$

Thus, the blocking probability (call congestion) perceived by a burst as well as a circuit is $(T_o - T_c)/T_o$.

Solving the system of equations given by (1) and (2) does not scale well for practical values of K and/or M. A scalable fixed-point approximation is developed next by reducing the dimension of the underlying state-space Λ.

2.2. A Scalable Fixed-Point Approximation

For large K and/or M, we consider a fixed-point approximation based on the usual one-dimensional Engset loss model where the mean off period is increased to account for frozen sources. According to the rationale underpinning this approximation, we define a modified mean off period, which is denoted as $1/\lambda^*$ and given by

$$\frac{1}{\lambda^*} = (1 - p)\lambda + p\left(\frac{\lambda_b}{\lambda}\frac{1}{\mu_b} + \frac{1}{\lambda}\right), \tag{3}$$

where p is the probability that all K servers are busy at the time instant just before an arrival.

Equation (3) can be explained as follows. An arrival is not blocked with probability $1 - p$, in which case the mean off period is simply $1/\lambda$. This explains the first term in (3). Otherwise, an arrival is blocked with probability p, in which case it is: a burst with probability λ_b/λ, which results in a frozen source with mean off period $1/\lambda + 1/\mu_b$; and, a circuit with probability λ_c/λ, which results in a mean off period $1/\lambda$. Weighting $1/\lambda + 1/\mu_b$ and $1/\lambda$ by the appropriate probabilities gives the second term in (3).

Since our approximation is based on the usual one-dimensional Engset loss model, we must also define a modified mean on time, which is denoted as $1/\mu^*$ and given by

$$1/\mu^* = \frac{\lambda_b}{\lambda}\frac{1}{\mu_b} + \frac{\lambda_c}{\lambda}\frac{1}{\mu_c}. \tag{4}$$

The probability that all K servers are busy at a time instant just before an arrival is given by

$$p = \text{Eng}(\lambda^*, \mu^*, M - 1, K) \triangleq \frac{\binom{M-1}{K}(\lambda^*/\mu^*)^K}{\sum_{i=0}^{K}\binom{M-1}{i}(\lambda^*/\mu^*)^i}, \tag{5}$$

which is the usual Engset formula.

The relation between p and $1/\lambda^*$ expressed by (3) and (5) defines a fixed-point equation. Consistent values for p and $1/\lambda^*$, may be computed with the following repeated substitution algorithm. Let $\lambda^*(0) = \lambda$. While $|\lambda^*(n) - \lambda^*(n-1)| > \epsilon$, $n \geq 1$, generate another iteration such that

$$1/\lambda^*(n + 1) = 1/\lambda + \text{Eng}(\lambda^*(n), \mu^*, M - 1, K)/\mu^*. \tag{6}$$

It is now proved that the repeated substitution algorithm must converge to the unique fixed-point of (3).

Fact 1 *Iterating according to* $1/\lambda^*(n+1) = 1/\lambda + \mathit{Eng}(\lambda^*(n), \mu^*, M-1, K)/\mu^*$ *with* $\lambda^*(0) = \lambda$ *converges to a unique fixed-point.*

Proof: Fixed-point uniqueness is straightforwardly proved by using the mean value theorem and establishing a contradiction where two distinct fixed-points cannot exist.

To prove convergence, we proceed as follows. Observe that the transformation from $\lambda(n)$ to $\lambda(n+1)$ is defined by the function $\Gamma(x)$, where $\Gamma(x) = \lambda\mu^*/\big(\mu^* + \lambda\text{Eng}(x, \mu^*, M-1, K)\big)$, $x \geq 0$. As $\text{Eng}(x, \mu^*, M-1, K)$ is increasing with x, $\Gamma(x)$ is a decreasing function. Namely, for any $x' \geq 0$ such that $x' < x$, $\Gamma(x') > \Gamma(x)$.

By (6), $\lambda^*(0) = \lambda > \lambda^*(1)$ and $\lambda^*(0) = \lambda > \lambda^*(2)$. In fact, $\lambda > \lambda^*(n)$ for all $n > 0$. As $\Gamma(x)$ is a decreasing function, $\lambda^*(0) > \lambda^*(1)$ implies $\lambda^*(2) > \lambda^*(1)$. Hence, $\lambda^*(0) > \lambda^*(2) > \lambda^*(1)$, and for similar reasoning $\lambda^*(1) < \lambda^*(3) < \lambda^*(2)$. In general, $\lambda^*(n) > \lambda^*(n+2) > \lambda^*(n+1)$, for n even, and $\lambda^*(n) < \lambda^*(n+2) < \lambda^*(n+1)$, for n odd.

Therefore, the sequence $\{\lambda^*(2n) : n \geq 0\}$ is decreasing and the sequence $\{\lambda^*(2n+1) : n \geq 0\}$ is increasing, as depicted in Fig. 1.

As $\text{Eng}(x, \mu^*, M-1, K)$ is strictly concave, both sequences must converge to a unique fixed-point. ■

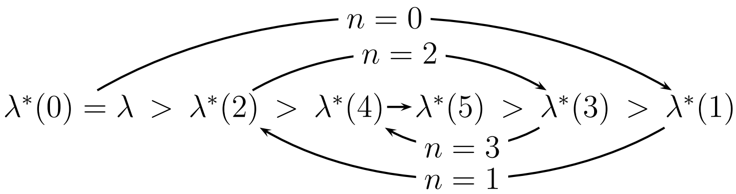


Figure 1. Depiction of the initial sequence of iterations

We remark that in writing (4), we have assumed that off periods in our fixed-point approximation are exponentially distributed. However, in our fixed-point approximation, off periods are hyper-exponentially distributed. In particular, an off period is exponentially distributed with mean: $1/\mu_b$ with probability λ_b/λ; and, with mean $1/\mu_c$ with probability λ_c/λ. It seems reasonable to assume off periods are exponentially distributed in our approximation because of its close resemblance to an Engset system, which is known to be insensitive to the distribution of on and off periods [11]. This is particularly evident for low blocking, where the presence of frozen states is insignificant.

3. NUMERICAL PERFORMANCE EVALUATION

In this section, we quantify the accuracy of a our approximation. We then test the sensitivity of the continuous time Markov chain described in Subsection 2.1 as well as our approximation to non-exponentially distributed on and off periods.

To test sensitivity, we implemented simulations for two cases: gamma distributed on periods and exponentially distributed off periods; and, gamma distributed on and off periods. We also implemented a simulation for exponentially distributed on and off periods to verify the correctness of computing blocking as described in Subsection 2.1. For gamma distributed on and/or off periods, we fitted commensurate means and considered three different values of the shape parameter associated with the gamma distribution. We considered $M = 10$, $K = 10$ and ensured the proportion of OBS and OCS traffic was equal; that is, $\lambda_b = \lambda_c$. In regards to the mean on period, we considered two cases: $\mu_b = 10^4\mu_c$; and, $\mu_b = 10^2\mu_c$.

We are interested in plotting blocking probability as given by simulation, our approximation and the continuous time Markov chain against the normalized traffic intensity, which is defined as $(M/K)(\lambda_b/\mu_b + \lambda_c/\mu_c)$.

Our numerical results are presented in Fig. 2. These results show that although blocking is not completely insensitive to the distribution of on and/or off periods, as in the usual Engset loss model, the sensitivity is mild enough to facilitate reasonable engineering approximations for the case of gamma distributed on and/or off periods. These results also show that our approximation is quite accurate over the range of practical blocking probabilities.

4. DIMENSIONING

In this section, we consider dimensioning a hybrid optical switch. This involves determining the minimum number of wavelengths required to satisfy a prescribed blocking probability for a nominal offered load that has been specified by a service provider.

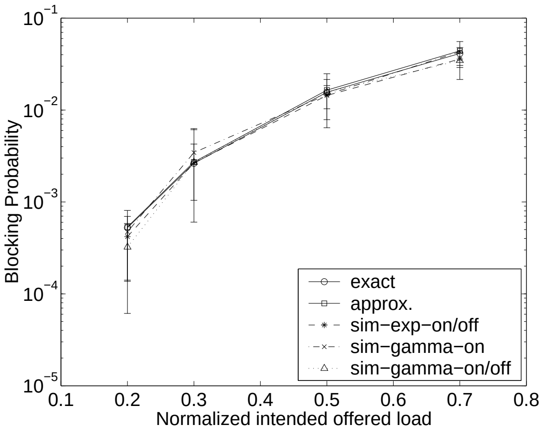
Since we have considered a hybrid optical switch that is fed by a *finite* number of sources (thus we have a state-dependent arrival process), we are faced with a dimensioning problem where offered load is dependent on blocking. To dimension properly, we would need to compute offered load as a function of blocking, which appears to be a difficult problem to solve analytically. We remark that this problem does not arise in an Erlang system because offered load is independent of blocking.

As an approximation for this dimensioning problem, we propose to dimension in terms of *intended offered load*, which is independent of blocking and defined as $M(\rho_b + \rho_c)/(1 + \rho_b + \rho_c)$, where $\rho_b = \lambda_b/\mu_b$ and $\rho_c = \lambda_c/\mu_c$. In particular, we use intended offered load as an approximation for offered load, and increment the number of wavelengths until a prescribed blocking probability is satisfied. Each time the number of wavelengths is incremented, blocking can be computed via: the continuous time Markov chain described in Subsection 2.1; or, for large values of K and/or M, our approximation can be used.

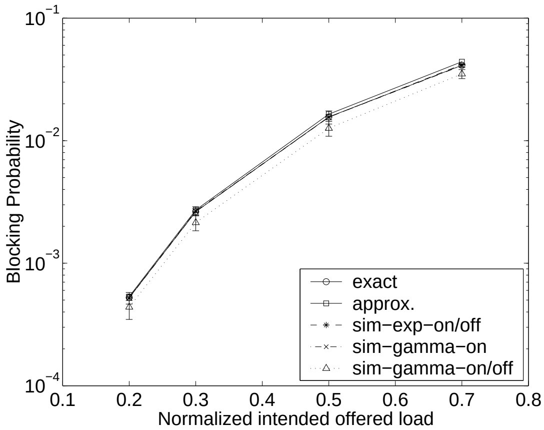
The accuracy of our dimensioning procedure relies on the validity of approximating offered load with intended offered load. It can be verified that intended offered load is equal to offered load (denoted as T_o in Subsection 2.1) for zero blocking. For non-zero blocking, this is not the case, and we thus consider a numerical example to quantify the error in approximating offered load with intended offered load.

In particular, we considered $M = 15$, $\mu_b = 10^2\mu_c$ and chose λ_b and λ_c to ensure $\rho_b = \rho_c = \rho$. We considered three cases: $\rho \in \{0.1, 0.2, 0.3\}$, and dimensioned for several blocking probabilities in the range 0.1 to 10^{-7}. We used the continuous time Markov chain described in Subsection 2.1 to compute blocking each time the number of wavelengths was incremented.

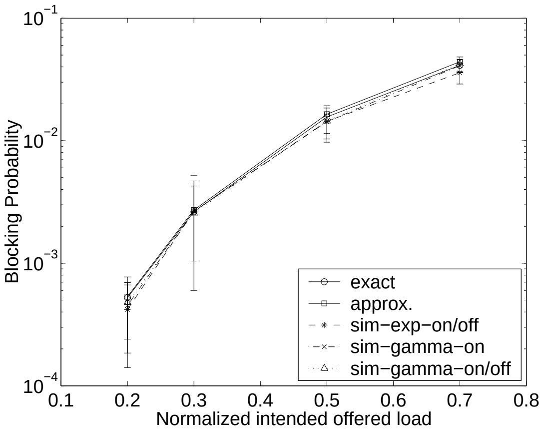
In Fig. 3(a), we plot the minimum number of wavelengths required to satisfy a range of blocking probabilities, while in Fig. 3(b), we show that intended offered load appears to be a valid approximation of offered load as long as blocking is less than about 0.1. For block-



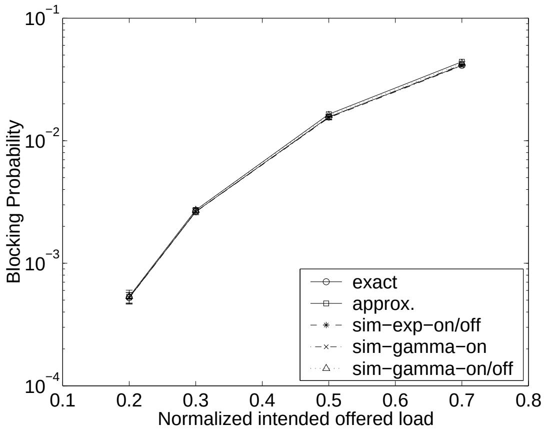
(a) $M = 10$, $K = 5$, $\mu_b = 10^4\mu_c$, $\lambda_b = \lambda_c$, shape parameter of gamma distribution = 0.1



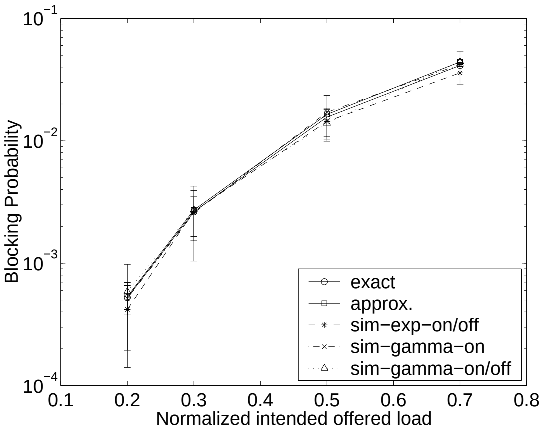
(b) $M = 10$, $K = 5$, $\mu_b = 10^2\mu_c$, $\lambda_b = \lambda_c$, shape parameter of gamma distribution = 0.1



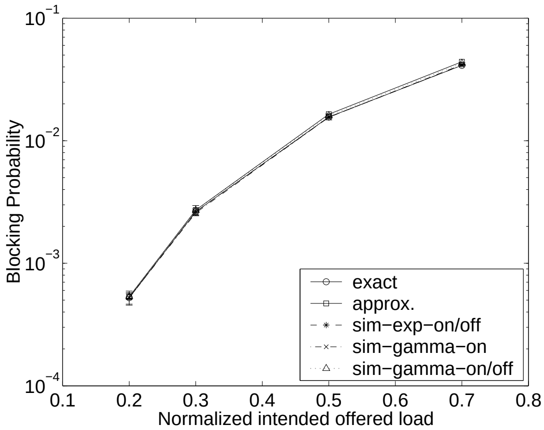
(c) $M = 10$, $K = 5$, $\mu_b = 10^4\mu_c$, $\lambda_b = \lambda_c$, shape parameter of gamma distribution = 2,



(d) $M = 10$, $K = 5$, $\mu_b = 10^2\mu_c$, $\lambda_b = \lambda_c$, shape parameter of gamma distribution = 2



(e) $M = 10$, $K = 5$, $\mu_b = 10^4\mu_c$, $\lambda_b = \lambda_c$, shape parameter of gamma distribution = 10



(f) $M = 10$, $K = 5$, $\mu_b = 10^2\mu_c$, $\lambda_b = \lambda_c$, shape parameter of gamma distribution = 10

Figure 2. Results of numerical evaluation

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