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2004-6

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Technical Report UTD/EE-01/2004

June 2004

Threshold-based Blocking Differentiation in Circuit-Switched WDM Networks

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Abstract—**This paper introduces a centralized admission control mechanism, referred to as Threshold-based Blocking Differentiation (*TBDiff*), to differentiate the blocking probability experienced by various service classes in a circuit switched WDM network. The mechanism is based on multiple class-thresholds that indicate the minimum amount of capacity that must be available, prior to accommodating a request for a given service class.**

The performance of *TBDiff* is studied by means of an analytical framework and also an event-driven simulator. The results show a thorough matching of the analytical and simulation results and also demonstrate that high blocking differentiation among service classes can be obtained, without excessively increasing the overall (average) network blocking probability.

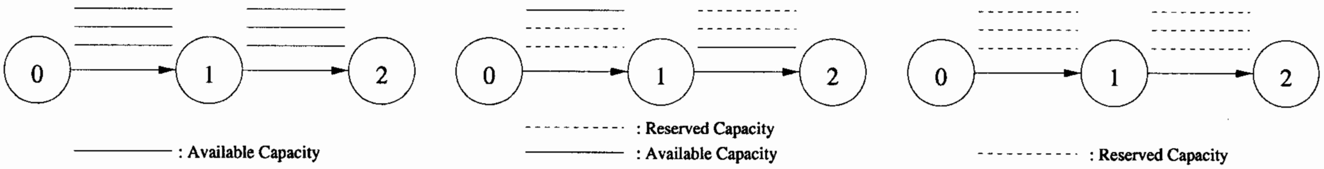
I. INTRODUCTION

Wavelength Division Multiplexed (WDM) networks offer the possibility of establishing multiple optical circuits, often referred to as *lightpaths* [1], to accommodate client traffic by reserving wavelengths. While the bandwidth offered by the wavelengths has reached unprecedented transmission capacities in the order of tens of Gb/s, the network traffic has also increased steadily over the years. Services are emerging nowadays that may require fast end-to-end transfer of huge data sets [2], [3]. Cost efficient solutions to achieve these fast transfers are expected to be based on circuit provisioning for the data set transfer duration. As the number of requests increases, inevitably, some requests may be blocked due to the finite bandwidth available on the fiber links. Lightpath requests may be blocked at the optical layer, when wavelengths are unavailable in some of the network links. Other sub-wavelength circuit requests, like SONET/SDH tributary signals and MPLS [4] with bandwidth guaranteed connections, may be blocked at the electronic layer.

Thus, in circuit switched networks that offer multiple classes of service to the client requests, it is essential to provide mechanisms that differentiate the blocking experienced by these requests. High priority requests must be ensured to experience the highest probability of being serviced, i.e., lowest blocking probability, whereas low priority requests may suffer higher blocking. Different approaches have been proposed for providing blocking differentiation according to the client's service class. Reference [5] achieves blocking differentiation for different service classes by adopting a QoS-based resource allocation scheme. In particular, routing and resource allocation in [5] are based on the client-specific quality parameters. Reference [6] proposes a method for achieving blocking differentiation by assigning different delay times to different service classes. Reference [7] achieves blocking differentiation by preempting already accommodated low priority requests (optical bursts). Reference [8] presents an approach for providing proportionally differentiated blocking probability to multiple service classes.

This paper proposes an alternative way to differentiate the blocking of requests in circuit switched WDM networks. Circuits may require either an entire wavelength or sub-wavelength bandwidth fractions. The admission control mechanism is based on a predetermined threshold assigned for each service class in the network and, thus, this mechanism is referred to as *Threshold-based Blocking Differentiation*, or *TBDiff* for short. Unlike most of the blocking differentiation mechanisms in the literature, *TBDiff* is based on simple thresholds. A connection of a specific service class is admitted into the network only if the available capacity for the connection is above the predetermined threshold value of that service class. *TBDiff* is also practically implementable as the network operators need to only set the proper thresholds to achieve significant blocking differentiation among different service classes.

In this paper, *TBDiff* is modeled using an analytical framework based on the celebrated Erlang's reduced load approximation method [9], [10], combined with the more recent model extension [11]. For validation, results of the analytical model are compared with the results of the simulations on the NSFNET topology. The comparison shows a close match of the low complexity analytical framework with the simulation results. The results also reveal that with the proposed simple and low-complexity *TBDiff*, it is possible to achieve significant blocking differentiation under various network loads. Moreover, *TBDiff* increases the overall (average) blocking probability only marginally, when compared to the classless network scenario.



(a) Both S_0 and S_1 are admitted

(b) S_0 is admitted while S_1 is rejected

(c) Both S_0 and S_1 are rejected

Fig. 1. Illustrative example

II. THE THRESHOLD-BASED BLOCKING DIFFERENTIATION (*TBDiff*) MECHANISM

This section describes the centralized *TBDiff* mechanism chosen to differentiate the blocking probability of multiple service classes.

A WDM network can be modeled as a graph $G(V, E)$, where V is the set of nodes and E is the set of edges. The graph can either represent:

- Physical Topology: in this case, the edges in E correspond to the physical lines, each one carrying W wavelengths; (or)
- Virtual Topology: in this case, each edge in E corresponds to the M pre-established lightpaths, each one able to multiplex g connections (e.g., LSPs in MPLS networks, tributaries in SONET, etc).

In order to explain the *TBDiff* mechanism, all assumptions made about the network and traffic are explained below:

1) Each one of the J links, $J = |E|$, has (integer) capacity C [1]. The capacity can correspond to either the wavelength capacity (i.e., $C = W$) or the sub-wavelength capacity (i.e., $C = M \cdot g$), depending on the topology represented.
2) Each network node is assumed to have full wavelength conversion capabilities (Physical Topology case) or full traffic grooming capabilities (Virtual Topology case).
3) Requests to reserve network capacity for data transmission arrive dynamically in the network. The network capacity can be of the order of a wavelength (Physical Topology case) or sub-wavelength (Virtual Topology case).
4) Requests between each source-destination pair are classified into K service classes, $S_0, S_1, \ldots S_{K-1}$, with their priorities sorted in descending order.
5) A pre-defined threshold parameter t_i is assigned to each service class $i = 0, 1, \ldots K-1$, such that:

$$0 \leq t_i < C \qquad \forall i = 0, 1, \ldots (K-1). \qquad (1)$$

$$t_i < t_{i+1} \qquad \forall i = 0, 1, \ldots (K-2). \qquad (2)$$

The role of the threshold parameter is to decide whether the requests should be blocked or not, as will be explained in the next sub-section.

A. *TBDiff Mechanism Description*

Once a request of a service class S_i between a source and a destination arrives in the network, the following steps are sequentially executed to reserve the network capacity:

1) A route R is selected to establish the circuit between the source and destination nodes.
2) The available (not reserved for transmission) capacity on route R ($\bar{C}(R)$) is evaluated as:

$$\bar{C}(R) = \min_{j:j \in R} \bar{C}(j) \qquad (3)$$

where $\bar{C}(j)$ is the available capacity on link j.
3) If $\bar{C}(R)$ is greater than the threshold value t_i of the service class S_i, then a wavelength (or a sub-wavelength) is selected and reserved along the route R.
4) If $\bar{C}(R)$ is less than or equal to the threshold value t_i of the service class S_i, then the request is blocked.

The reserved capacity is then freed at the end of data transmission.

B. *Illustrative Example*

The following example illustrates the implementation of *TBDiff*. Consider the tandem network (Fig. 1) consisting of 3 nodes and two unidirectional links. Each link has a capacity of 3 units. The network is assumed to have two service classes, namely S_0 and S_1 with the respective threshold values $t_0 = 0$ and $t_1 = 1$. The connections have to be setup from node 0 to node 2 along the route 0-1-2. A connection belonging to a service class S_i is admitted into the network only if the available capacity along the selected route is more than the threshold value (t_i) of S_i. In Fig. 1(a), all the network capacity is available along the selected route. Hence both the service classes S_0 and S_1 can be admitted in the network. In Fig. 1(b) only one unit of capacity is available on the selected route. Since $t_0 = 0$, class S_0 can be admitted while S_1 is blocked since at least two units of capacity ($t_1 = 1$) are required to admit S_1. In Fig. 1(c), none of the network capacity is available and hence both the service classes are blocked.

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[1] To simplify the formulation, it is assumed that every graph edge has the same capacity. However, the model can be easily extended to the case in which distinct edges are furnished with different amounts of capacity.

III. ANALYTICAL FRAMEWORK

This section presents the analytical framework for *TBDiff*. The framework is based on the analytical model presented in [9].

In order to derive the analytical framework, the following assumptions have been made:

- Requests for each service class S_i between a source-destination pair are always accommodated along a pre-computed route R between the source and the destination nodes.
- The request arrival process is assumed to be Poisson with arrival rate $\lambda_R(i)$ and each request requires one unit of network capacity.
- The request holding time can follow any arbitrary distribution with mean $1/\mu$.
- The wavelength (or sub-wavelength) that has to be reserved for transmission is randomly chosen among all the available wavelengths (or sub-wavelengths).

Each link is modeled as a $M/G/C/C$ system. The generalization of the request holding time distribution is possible due to the insensitivity of blocking experienced by requests in circuit switched networks [12]. Fig. 2 presents the Markov chain representing the birth-death process of the amount of available capacity on a link j. In Fig. 2, $\alpha_j(i,m)$ represents the arrival rate of requests for service class S_i on a link j when the amount of available capacity on link j is m.

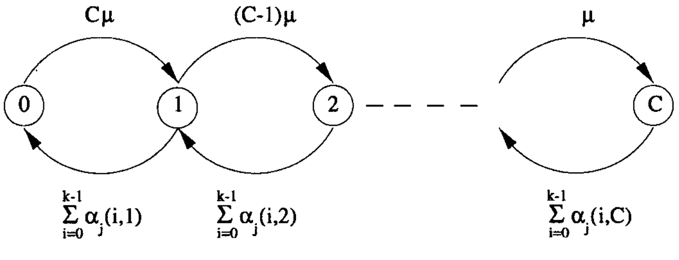

Fig. 2. Markov chain depicting the amount of available capacity on link j

The steady state probabilities of the amount of available capacity on link j is given by:

$$q_j(m) = \frac{C\mu \cdot (C-1)\mu \cdot \ldots (C-m+1)\mu}{\sum_{i=0}^{K-1} \alpha_j(i,1) \cdot \ldots \sum_{i=0}^{K-1} \alpha_j(i,m)} \, q_j(0) \quad (4)$$

and

$$q_j(0) = \left[1 + \sum_{m=1}^{C} \frac{C\mu \cdot (C-1)\mu \ldots (C-m+1)\mu}{\prod_{h=1}^{m} \sum_{i=0}^{K-1} \alpha_j(i,h)} \right]^{-1} \quad (5)$$

Let the amount of available capacity on the link j be represented by a random variable X_j. Let the amount of available capacity on route R for a service class S_i be represented by a random variable $X_R(i)$. The arrival rate $\alpha_j(i,m)$ of the service class S_i on a link j can be obtained by summing up the arrival rates of all S_i requests to be routed along link j. Hence

$$\alpha_j(i,m) = \begin{cases} 0 & m \le t_i \\ \sum_{R:j \in R} \lambda_R(i) \cdot P(X_R(i) > 0 | X_j = m) & \\ & m = t_i + 1, t_i + 2, \ldots C \end{cases} \quad (6)$$

where $\lambda_R(i)$ is the arrival rate of requests for class S_i along route R.

The probability that for the service class S_i there is at least t_i units of capacity available along route R, given that the capacity available on link j is m units, is obtained by the probability that the capacity available on any link (except j) of the route R is at least t_i units, i.e.,:

$$P(X_R(i) > 0 | X_j = m) = \prod_{s \in R, s \neq j} \left(1 - \sum_{k=0}^{t_i} q_s(k) \right). \quad (7)$$

The blocking probability for requests of the service class S_i along route R is then given by:

$$B_R(i) = 1 - \prod_{j \in R} \left(1 - \sum_{l=0}^{t_i} q_j(l) \right). \quad (8)$$

A. Blocking Probability Computation

The presented analytical model requires the solution of a number of non-linear coupled equations. Though the existence of an unique solution has not been proven, yet, for many practical cases it is possible to reach a solution through iterations. The iterative process stops when the numerical difference between the previous iterative solution and the current solution is smaller than an acceptable error $\epsilon > 0$. The iterative process is presented below:

1) For each route R, initialize the blocking probabilities of each service class i, $B_R(i) = 0 \;\; \forall i = 0, 1 \ldots K-1$.
2) Initialize the arrival rate of each service class S_i on each link j as follows:

$$\alpha_j(i,m) = \begin{cases} 0 & m \le t(i) \\ \sum_{R:j \in R} \lambda_R(i) & \texttt{else.} \end{cases} \quad (9)$$

3) Compute the distribution of the available capacity for each link using Eq. 4 and Eq. 5.
4) Compute the new arrival rate on each link using Eq. 6 and Eq. 7.
5) Compute the new blocking probabilities $\hat{B}_R(i)$ using Eq. 8.
6) If $max_R |B_R(i) - \hat{B}_R(i)| < \epsilon \;\; \forall i = 0, 1 \ldots K-1$ then terminate. If not, then $B_R(i) = \hat{B}_R(i)$ and go to step 3.

B. Computational Complexity Analysis

The calculation of the state dependent arrival rates (Eq. 4 and Eq. 5) for a given link requires $O(KC^2)$ operations or only $O(C^2)$ by parallel computation. Since this has to be done for each link, the computations have to be repeated J times, unless parallel computing is used. Hence the computation of state dependent arrival rates for all the links requires $O(JKC^2)$ operations. With the calculated state dependent arrival rates, the calculation of the blocking probability of a request of a service class S_i along route R (Eq. 8) requires $O(JC)$ operations. Thus, overall blocking probability computation for the requests of all the service classes requires $O(JKC^2)$ operations, or $O(C^2)$ operations when parallel computing is used.

The computational complexity is in agreement with the computational complexity of the model presented in [11], when the number of classes is one ($K = 1$).

IV. MODEL VALIDATION AND RESULTS

The performance evaluation of *TBDiff* is carried out on the graph presented in Fig. 3, which represents the NSFNET. The graph has 14 nodes and 38 links. The total capacity on each link is $C = 10$. (E.g., the presented results are valid for networks with a physical topology as the one shown in figure that has 10 wavelengths on each line.)

The requests arrive in the network as a Poisson process and the request holding time is exponentially distributed with unit mean. The requests are uniformly distributed across all the source-destination node pairs and among all the service classes. Each request is routed along the shortest path in terms of number of hops. For all results, the simulation time is set to achieve a confidence interval value of 10% or better, at 95% confidence level.

The collected results are the blocking probability for each service class, the mean blocking probability averaged over different service classes, and the blocking probability for a classless scenario, in which the requests are blocked only when the capacity is not available.

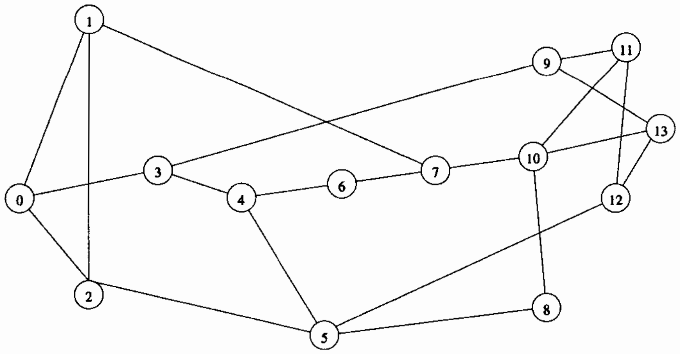

Fig. 3. Graph used for simulation

A. *Effect of Threshold Values*

In order to practically implement *TBDiff*, it is necessary to select suitable threshold values. Each threshold value affects the blocking probability gap between the different service classes. In this sub-section, two service classes ($K = 2$) are assumed in the network. The threshold value of the high priority class, S_0, is $t_0 = 0$ (i.e., requests are blocked only when capacity is unavailable), while the threshold value of the low priority class, S_1, is varied. The network load is kept constant at 100 Erlangs. Results are presented in Fig. 4.

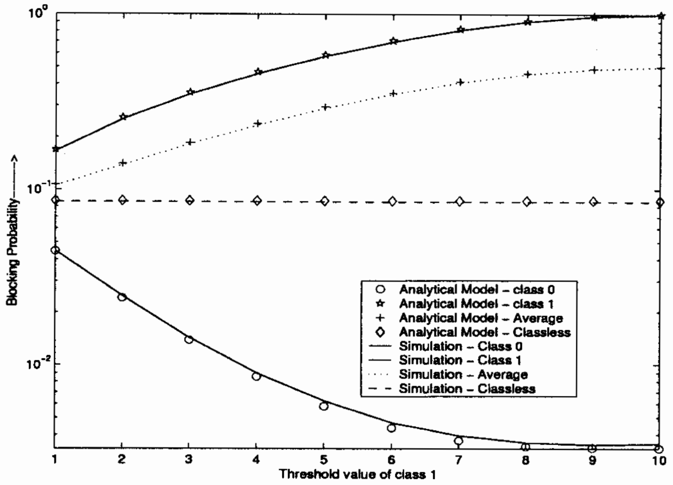

Fig. 4. Blocking probability for two service classes for different values of threshold parameter in class S_1

The analytical model thoroughly fits the simulation results. The results show that, even when $t_1 = 1$, the blocking probability of the two classes can be differentiated significantly. By setting different values for t_1, the network operator may be able to obtain the desired degree of blocking differentiation among the service classes.

By comparing the average blocking probability with the blocking probability of the classless scenario, it is possible to evaluate if the high priority requests are effectively benefitted from the increased blocking experienced by the low priority requests. Fig. 4 also shows that for low values of t_1, the blocking differentiation is achieved with a contained increase of the overall (average) network blocking. However, to achieve high blocking differentiation (i.e., for high t_1), *TBDiff* might excessively block class S_1 requests.

B. *Effect of Offered Load*

The differentiation in terms of blocking probability is now evaluated when the request arrival rate, or load, changes. Fig. 5 plots the blocking probabilities of two service classes (class S_0 and class S_1) for various network loads. The threshold parameters are set to $t_0 = 0$ and $t_1 = 1$. Even when the load changes, the blocking probabilities of the two service classes are differentiated, providing minimal blocking for high priority connections and higher blocking for low priority connections. Moreover, the analytical model results perfectly match the simulation results, for any network load. Finally, the gap between the average blocking probability and the blocking probability of the classless scenario is marginal, indicating that the requests do not suffer increased blocking due to *TBDiff.*

Fig. 6 illustrates the blocking probability of four service classes at various network loads. The threshold values are fixed to $t_i = i$, for $i = 0, 1, 2, 3$. Although the complexity of the model has increased with the number of classes, the analytical

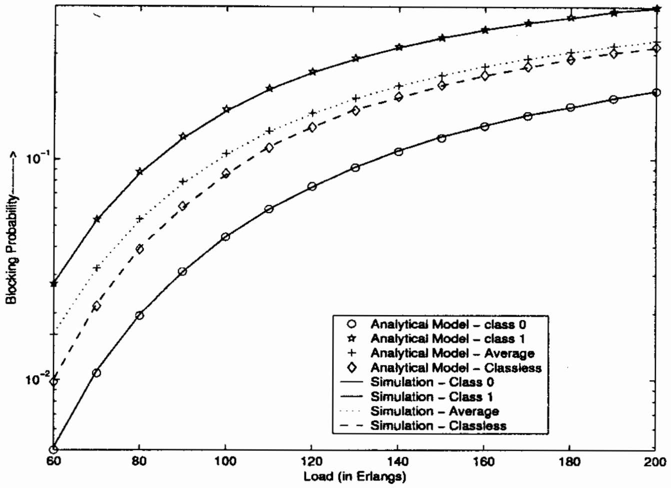

Fig. 5. Blocking probability vs. network load for two service classes

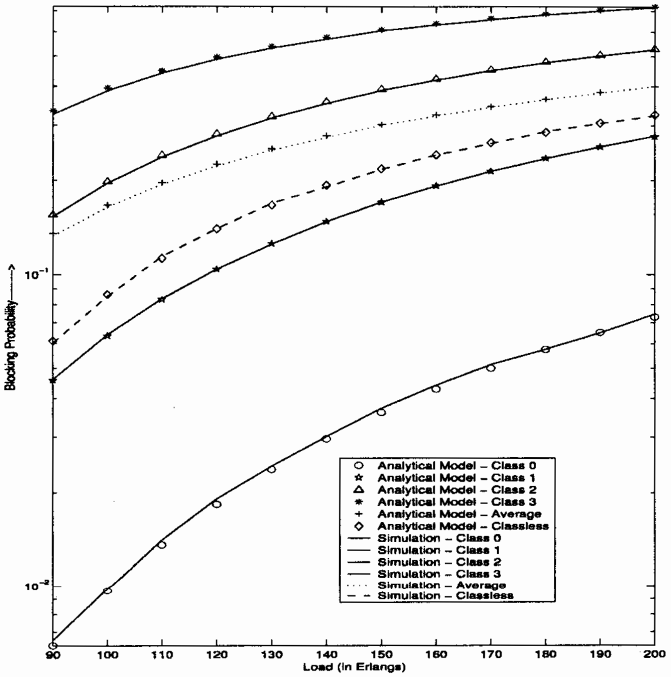

Fig. 6. Blocking probability vs. network load for four service classes

results perfectly agree with the simulation results. The level of blocking differentiation is maintained at different network loads. However when the number of classes increases, the low priority requests tend to have very high blocking, in order to allow the higher priority requests into the network.

V. CONCLUSION AND FUTURE WORK

In this paper, a novel admission control mechanism, called Threshold-based Blocking Differentiation (*TBDiff*), for differentiating the blocking probability experienced by various service classes is proposed. *TBDiff* is based on predefined threshold values assigned for different service classes. The request of a service class is blocked, if the available capacity is below the threshold value assigned for that service class.

A centralized version of the admission control mechanism is presented and discussed. An analytical framework for *TBDiff* is proposed that may be used in WDM networks with wavelength conversion capabilities, as well as in connection-oriented networks with sub-wavelength traffic grooming capabilities. The obtained analytical results closely match the simulation results and support the ability of *TBDiff* to provide a good degree of blocking differentiation among various service classes. Moreover, the overall (average) network blocking probability is shown to be only marginally increased by *TBDiff*, when compared to the classless scenario.

It is expected that *TBDiff* may be extended to work in other networking scenarios, where, a limited network capacity is to be shared among multiple service classes of client requests. The authors are currently investigating how to extend *TBDiff* to effectively work in wavelength-constrained networks, i.e., networks in which wavelength conversion is not available.

VI. ACKNOWLEDGMENTS

The work was partially supported by NSF under contract # ANI-0082085, CPqD, and Italian Ministry of University (MIUR) under FIRB project "Enabling platforms for high-performance computational grids oriented to scalable virtual organizations" (contract n. RBNE01KNFP).

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