Performance Analysis of Traffic-Groomed Optical Networks Employing Alternate Routing Techniques

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Abstract. Recent advances in telecommunication networks have allowed WDM to emerge as a viable solution to the ever-increasing demands of the Internet. In a wavelength-routed optical network, traffic is transported over lightpaths, which exclusively occupy an entire wavelength on each hop of the source-destination path. Because these networks carry large amounts of traffic, alternate routing methods are designed in order to allow traffic to be properly re-routed from source to destination in the event of certain events, such as link blocking or failure. In this paper, we consider a tandem traffic-groomed optical network, modeled as a multi-level overflow system, where each level represents a wavelength between adjacent nodes. The queueing network is analyzed using a combination of methods. As will be shown, the decomposition method provides a good approximate analysis of large overflow systems supporting traffic from multiple sources.

1 Introduction

In a wavelength-routed optical network, traffic is transported over lightpaths, which exclusively occupy an entire wavelength on each hop of the source-destination path. Traffic grooming divides the bandwidth of a lightpath into lower sub-rate units, so that it can carry traffic streams transmitted at lower rates. A traffic stream uses one or a multiple of these sub-rate units. The lowest sub-rate stream carried, hereafter referred to as a sub-wavelength unit, defines a lightpath's granularity.

Because these networks carry large amounts of traffic, alternate routing methods are designed in order to allow traffic to be properly re-routed from source to destination in the event of certain events, such as link blocking, or failure. A call arriving at a network is assigned a primary path, upon which it initially attempts to be routed. If the call cannot be routed on this path, then it is re-routed to an alternate path. If there are multiple alternate paths available, then they are attempted in either a random or specific order until the call is established. The call is blocked from the network if the primary and alternate paths cannot carry it.

In this paper, we consider a tandem traffic-groomed optical network composed of N nodes linked in series. Each optical node is an add/drop multiplexer (ADM). The network supports traffic from multiple sources, each with a resource requirement measured in sub-wavelength units. We assume that a number of lightpaths have been established. A path between two nodes may be served by a single direct lightpath or a sequence of lightpaths. Traffic bifurcation is permitted, meaning calls are allowed to use sub-rate traffic streams belonging to different wavelengths.

We model the optical network as a multi-level overflow system, where each level represents a single wavelength between adjacent nodes. Within each level is a tandem queueing network of multi-rate Erlang loss nodes, where a customer occupies a number of servers on one or more adjacent nodes.

The analysis of overflow systems, where blocked calls arriving to a primary Erlang loss system overflow to a secondary system, has been extensively studied. The majority of this work has focused on systems where all calls require a single resource[1],[2],[5],[6],[7],[9],[11],[12],[13],[15].

In this work, we decompose the queuing network into subsystems, where each subsystem is analyzed using a combination of methods developed by Nilsson et. al [14], Frederick and Hayward, and Basharin and Kurenkov [3]. As will be shown, the decomposition method provides a good approximate analysis of large overflow systems supporting traffic from multiple sources.

Washington et. al [19] and [20] proposed a decomposition algorithm for the analysis of tandem optical networks, whereby the queueing network was decomposed into subsystems, each consisting of two adjacent nodes. In this work, we consider networks allowing for overflow analysis.

The remainder of the paper is organized as follows. Section 2 describes the queuing network model used to calculate call blocking probabilities in the traffic-groomed optical network. Section 3 describes the decomposition algorithm. Section 4 presents numerical comparisons between the algorithm and simulation model. Finally, section 5 concludes the paper.

2 The Queueing Network Model

We consider a traffic-groomed optical network composed of N nodes linked in series. Each link between adjacent nodes is composed of W wavelengths. Each wavelength contains s sub-wavelength units, where s is assumed to be large.

Figure 1 illustrates a four-node optical network with W=3 wavelengths on each link. The following lightpaths have been established: *0-3* on wavelength *1*, *0-2* and *2-3* on wavelength *2*, and *0-1*, *1-2*, and *2-3* on wavelength *3*. Due to the traffic bifurcation assumption, each of the three wavelengths in Figure 1 logically represents the combining of multiple wavelengths between the same source destination pair. In other words, all wavelengths where calls have a direct path from node 0 to node 2, for example, are grouped to form a single pool of resources from which sub-rate streams are allocated to each call on the direct path. Calls arrive at any node i, i=0, 1, 2 and are destined for any node j, j=1, 2, 3, where $j>i$. All calls, irrespective of their source-destination path, are grouped into R classes. Each class r call, r=1, 2,…, R, has an associated demand, d_r, measured in sub-wavelength units.

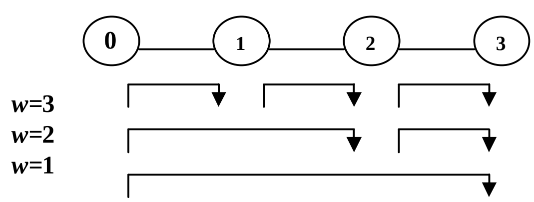

Fig. 1. A four-node, three-wavelength optical network and all source-destination paths

A class r call arriving at node i with destination j, $j>i$, is initially offered to the direct lightpath between nodes i and j, if there is any. The call will be accepted on the direct lightpath, which we will refer to as the primary path, if d_r sub-wavelength units are available on the same wavelength along links i+1, i+2, …j. These sub-wavelength units are simultaneously allocated on all links upon call arrival. Upon the call departure, all d_r sub-wavelength units are simultaneously released along each link of the source-destination path. If a call cannot be serviced on its primary path, the call is offered to its pre-determined alternate paths in a sequential fashion. The alternate paths may traverse one or more lightpaths. This process repeats until the call is either accepted on one of its alternate paths or is blocked.

We model the optical network of Figure 1 as a W-level overflow system, where each level represents the lightpaths existing on a wavelength and each lightpath is represented by a multi-rate loss node with $n=s$ servers. Figure 2 illustrates the queueing network model. The solid lines represent random Poisson traffic arriving to the node. The dashed lines represent overflow traffic arriving to the node from a previous wavelength. A server represents a sub-wavelength unit. Each customer in the queueing network represents a call. Customers arrive at any node on any wavelength w, w=1,2,…W, with Poisson rate $\lambda_{w,r}$ and exponential service rate $\mu_{w,r}$. In addition to the local arriving traffic, traffic overflowing from wavelength w-1 may also arrive to the node.

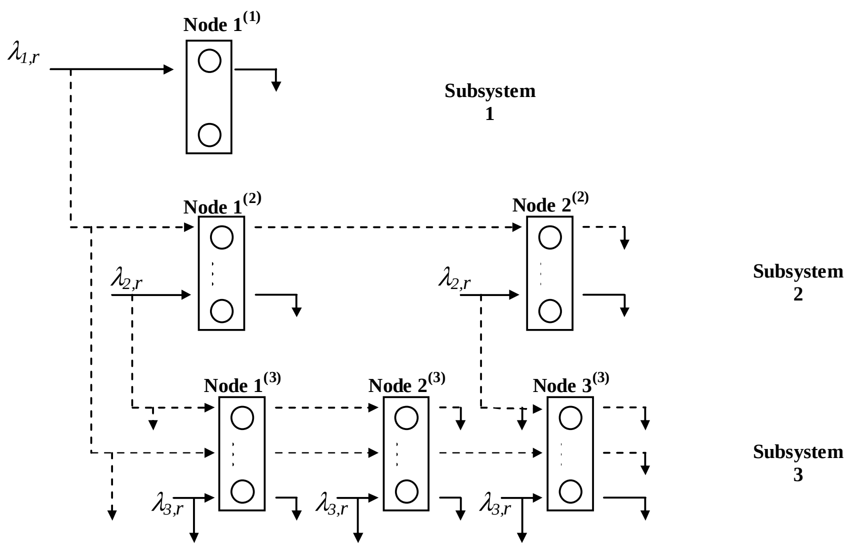

Fig. 2. The queueing network and the individual subsystems

A class r local customer arriving to a node at wavelength w simultaneously occupies d_r servers and simultaneously releases them at the time the customer leaves the network. If there are not enough free servers available, the customer overflows to the pre-determined alternate node(s) on wavelength w+1. If the customer is accepted on the alternate path, then it simultaneously occupies and releases d_r servers on each node of the alternate path. If there are not enough free servers available at wavelength w+1, the customer overflows to the alternate node(s) on wavelength w+2, and so forth. Upon reaching wavelength W, if the class r customer finds an insufficient number of servers available, the customer is blocked, i.e. lost. We note that, at wavelength W, random Poisson customers arriving to any node for service are blocked, i.e. do not overflow, if they cannot be serviced at the node.

3 The Decomposition Algorithm

In this section, we present the decomposition algorithm developed for the analysis of the above-described queueing network. The algorithm first decomposes the network into W subsystems. Each subsystem is then analyzed as a single-wavelength network composed of the nodes that correspond to the lightpaths established over the wavelength. First, we describe the two node types in the network and follow this with the decomposition algorithm.

3.1. Types of Network Nodes

As previously stated, the queueing network consists of levels of nodes, representing lightpaths on specific wavelengths in the original network. There are two types of nodes that exist in the network. The analysis of each is described below.

3.1.1. Nodes Supporting Poisson Traffic. The first node supports Poisson traffic only. That is, there is no overflow traffic arriving to the node. This is the case for traffic arriving to node *1* on wavelength *1*, in Figure 2. The node supports traffic from R classes, each with a demand of d_r servers, $r=1,2,\ldots,R$. The analysis of the node is performed using the recursion developed by Nilsson et. al. Let m denote the maximum number of servers in the node. In addition, let k denote the number of free servers in the node. The function $\beta(m,k)$, defined as the probability that m-k servers are busy in the node, is determined as

$$\beta(m,k)= \beta(m-1,k-1)/[1+(1/m)\sum_r A_r d_r \beta(m-1, d_r-1)\,] \,. \qquad \textbf{(1)}$$

$$\beta(m,0)= (1/m) \sum_r A_r d_r \beta(m-1, d_r-1)\, [/1+(1/m)\sum_r A_r d_r \beta(m-1, d_r-1)\,] \,. \qquad \textbf{(2)}$$

$A_r=A_{w,r}=\lambda_{w,r}/\mu_{w,r}$ is the offered traffic of a class r customer. The blocking probability is determined as

$$b_r=\sum_{j=0}^{d_r-1} \beta(m, j) \quad . \qquad \textbf{(3)}$$

Nodes Supporting Overflow and Poisson Traffic. The second type of node supports both local arriving Poisson traffic and traffic overflowing from a previous subsystem, such as those on wavelength *2* of Figure 2. If either traffic cannot be serviced on the node, it overflows to the subsequent wavelength until it is blocked. We note that there may be overflow traffic from more than one node.

Consider, for example, the traffic arriving to node $1^{(2)}$ in Figure 2. The node supports R classes of traffic overflowing from wavelength *1*, as well as R classes of local Poisson traffic. As noted before, the overflow traffic is not Poisson. In order to analyze the node, we must determine an equivalent Poisson flow to represent the overflow traffic. We propose the following approximation.

The mean of the offered traffic of each class r overflow customer, M_r, is determined using basic overflow analysis methods. However, the variance, V_r, cannot be determined as such, due to the fact that the overflow of each class r customer at node *1* on wavelength *1* is not independent of the overflow from the other classes. To determine V_r, we assume that each class r customer arrives to an independent set of primary servers, N_r, on wavelength *1*. Each customer, regardless of class and original demand, requires one server. The blocking experienced by the class r customer is equal to the blocking experienced by a class r customer in the original node. This analysis allows us to analyze each class r customer using the Erlang-B equation, such that we can determine an equivalent number of servers that would produce the same blocking probability, assuming single-server demands, as in the original system.

The value of N_r is determined as follows. For each class r, N_r is initialized to zero. We define b_{test} as the current value of the blocking probability of the single-flow equivalent system, such that

$$b_{test}=E_r(A_r, N_r) \ . \qquad \textbf{(4)}$$

Beginning with N_r=0, b_{test} is determined using (4). The difference between b_{test} and b_r is calculated. If the difference is less than a pre-specified value, then the current value of N_r is a suitable approximation for the single-flow system. Otherwise, if b_{test} is greater than b_r, the value of N_r is too low, and it is increased by a specific amount, referred to as *delta*. If b_{test} is lower than b_r, N_r is too high, and it is decreased by *delta*. The value of *delta* is initialized to 1 and successively halved, depending on the difference between b_{test} and b_r. While the difference is higher, the value of *delta* remains unchanged. As the difference decreases, the value of *delta* is halved. This process is repeated until the difference between b_{test} and b_r is less than the pre-specified value.

At this point, we have determined the equivalent number of servers, N_r, for each class r customer, that would produce the blocking probability, b_r, experienced by the node of the previous subsystem, assuming each class r customer arrived to an independent group of servers with rate $A_{w,r}$ and requesting a single server. N_r is used to approximate the variance of each overflowing traffic stream as

$$V_r=1-M_r+(A_r/(N_r+1-A_r+M_r)) \ . \qquad \textbf{(5)}$$

The peakedness of each overflowing customer, Z_r, is defined as

$$Z_r=V_r/M_r \ . \qquad \textbf{(6)}$$

At this point, the equivalent Poisson traffic for the overflow traffic offered to the node is defined as M_r/Z_r. We now proceed to analyze the node using the equivalent and local Poisson traffic. Basharin and Kurenkov's approximation requires either the scaling of the maximum number of servers in the node or the demand of each class r call offered to the node. We note that, because multiple classes are considered in addition to the arrival of both overflow and local traffic to the node, the analysis requires the scaling of the call demands of the overflow traffic by the respective peakedness values, Z_r. The node is analyzed using (1), (2), and (3). It is to be noted that, the demands of each class r customer of the overflow and Poisson traffic may no longer be identical. As a result, we assume that $2R$ classes of traffic, with individual demands d_r, r=1, 2, …$2R$, arrive to the node.

3.2 The Decomposition Algorithm

We describe the decomposition algorithm using the four-node optical network modeled by the queueing network shown in Figure 2. The queueing network is decomposed into three subsystems, corresponding to the three wavelengths shown in Figure 1. Subsystem *1* represents the lightpath on wavelength *1*, subsystem *2* represents the lightpaths on wavelength *2*, and subsystem *3* represents the lightpaths on wavelength *3*. $A_r^{(x)} = \lambda_r^{(x)} / \mu_r^{(x)}$ is the offered traffic of a class *r* customer on subsystem *x*, where *x*=1,2,3. $M_{y,r}^{(x)}$ and $Z_{y,r}^{(x)}$ denote the mean and peakedness, respectively, of the offered traffic of a class *r* customer overflowing from node *y* of subsystem *x*. $\underline{A}_{y,r}^{(x)}$ and $\underline{d}_{y,r}^{(x)}$ denote the equivalent offered traffic and equivalent demand, respectively, of a class *r* customer overflowing to node *y* on subsystem *x*. Finally, $b_{y,r}^{(x)}$ is the blocking probability of a class *r* customer at node *y* of subsystem *x*. All blocking probabilities are initialized to zero.

Beginning with subsystem *1*, each subsystem is analyzed in sequence. Within a subsystem, each node is analyzed iteratively assuming link independence. For subsystem *1*, the only traffic arriving to the node is Poisson traffic. The blocking probabilities, $b_{1,r}^{(1)}$, are stored and the algorithm shifts to subsystem *2*.

At subsystem *2*, the algorithm begins with node *1*. The equivalent Poisson traffic for each class *r* customer overflowing from subsystem *1* is first determined, and the most recently calculated values for $b_{1,r}^{(1)}$ are determined. We note that the overflow traffic arriving to this node continues on to node *2*, if accepted. The equivalent demands of the overflow traffic are then determined. Because there is both Poisson and overflow traffic arriving to the node, the maximum number of servers per node is fixed and the demands of the overflow traffic are scaled by their corresponding peakedness.

At this point, we have a total of *2R* classes arriving to node *1* on wavelength *2*, *R* classes of overflow traffic with equivalent offered traffic $\underline{A}_{1,r}^{(2)}$ and equivalent demands $\underline{d}_{1,r}^{(2)}$, and *R* classes of local Poisson traffic with offered traffic $A_r^{(x)}$ and demands d_r. The node is analyzed and the algorithm shifts to node *2* on wavelength 2, which is analyzed in similar fashion.

At this point, a single iteration has completed within subsystem *2*. The algorithm executes successive iterations until the blocking probabilities of each node within the subsystem have converged within a tolerance, ε, which is set to 10^{-4}. Once the results have converged, the blocking probabilities of all source-destination paths within the subsystem are calculated by appropriately combining the results from each node. For example, the blocking probability of the class *r* renewal traffic on path (*0,3*) of subsystem *2* is $1-(1-b_{1,r}^{(2)})(1-b_{2,r}^{(2)})$. The algorithm then shifts to subsystem *3*.

At subsystem *3*, each node is analyzed in iteration, similar to subsystem 2, using the most recently calculated blocking probabilities from each node in subsystem *2*. Beginning with node *1* on wavelength *3*, the equivalent Poisson traffic for each class *r* customer overflowing from node *1* on wavelength *2* is determined. We note there now are a total of *2R* classes of overflow traffic offered to node *1* on wavelength *3*, *R* classes from the overflow path traversing both nodes *1* and *2* on wavelength *2*, and *R* classes from the local traffic traversing node *1*.

The algorithm executes successive iterations in subsystem 3 until the blocking probabilities of each node within the subsystem have converged within ε. Once the results have converged, the blocking probabilities of all source-destination paths within the subsystem are calculated by appropriately combining the results from each node. Because this is the last subsystem, the blocking is determined as follows. For local traffic on node *1* of wavelength *3*, the blocking probability is simply $b^{(3)}_{1,r}$, $r=2R+1,2R+2,\ldots, 3R$. The blocking experienced by a call in a previous subsystem, such as subsystem *1*, is $M^{(2)}_{1,r}\ [1\text{-}(1\text{-}b^{(3)}_{1,r})(1\text{-}b^{(3)}_{2,r})(1\text{-}b^{(3)}_{3,r})]/A^{(1)}_r$, $r=1,2,\ldots,R$. We note that the blocking for this path uses the offered traffic arriving from subsystem *2*, the original offered traffic to subsystem *1*, and the blocking probability of the call in subsystem *3*.

4 Numerical Results

In this section, we discuss the accuracy of the decomposition algorithm by comparing the results obtained to simulation data. For each case, we consider the four-ADM optical network of Figure 1, modeled by the *W*-level queueing network shown in Figure 2. Each link between two adjacent ADMs is composed of 3 wavelengths, each wavelength containing *s* servers.

All possible source-destination paths are considered and, for each path, the call is first offered to the direct lightpath between the source and destination node. If the call cannot be serviced on the direct lightpath, it overflows to its alternate paths sequentially, until the call is either accepted or blocked. We assume four classes of traffic, i.e. R=4, with demands of d_1=2, d_2=4, d_3=6, and d_4=8 servers.

The accuracy of the decomposition algorithm was evaluated under different cases, where the arrival rates and the number of servers vary. We assume, for presentation purposes, that the arrival rate of all class *r* calls, regardless of source-destination path, is λ_r. For each case, λ_1 was assigned the highest arrival rate, and the arrival rate of each successive class *r* call was decreased by a small amount from the previous as follows. We assume *s*=256 servers. Cases 1 and 2 set λ_1 to 8000 and 10000, respectively. For both cases, the arrival rate of each successive class *r* call was decreased by 500, and the service rate of all calls was set to 500.

Figures 3 and 4 show the results for wavelengths *1* and *2*, and wavelengths *3* when *s*=256 servers. Each figure plots the blocking probability of each source-destination path, labeled as (source, destination), as a function of the call class. In addition, the simulation results are plotted with a 95% confidence interval. We note that the simulation results for each class are plotted as lines. This was done for presentation purposes, to help illustrate the accuracy of the approximation. It is to be noted, however, that the actual points represent the simulated data.

We observe that, overall, the decomposition provides good accuracy for all cases. Tables 1 and 2 show the per-class and per wavelength relative errors for each case. As is shown, the average relative errors are fairly low, meaning that the decomposition algorithm has good accuracy.

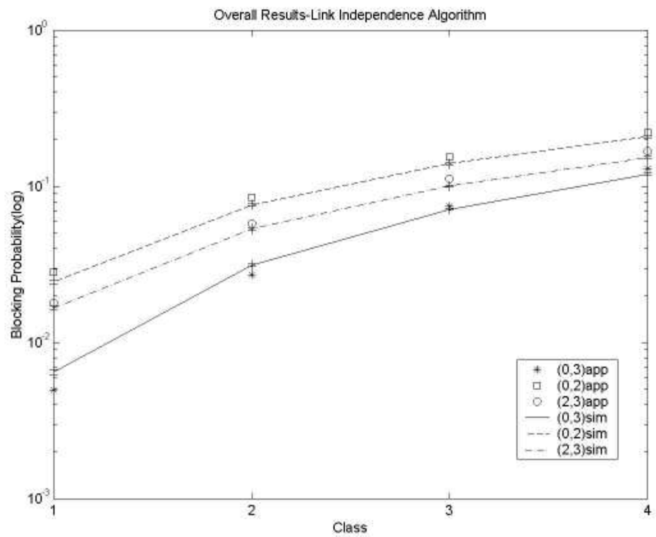

Fig. 3. Wavelength 1 and 2 results for *s*=256 servers

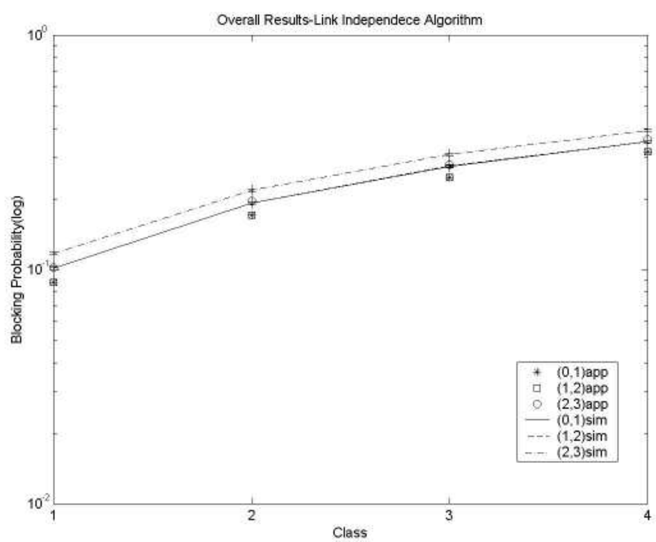

Fig. 4. Wavelength 3 results for *s*=256 servers.

Table 1. Per-class relative errors

		Class 1	Class 2	Class 3	Class 4
256	**Case 1**	0.041	0.031	0.027	0.025
	Case 2	0.046	0.027	0.019	0.015

Table 2. Per-wavelength relative errors

		Wave 1	Wave 2	Wave 3
256	**Case 1**	0.125	0.099	0.108
	Case 2	0.058	0.090	0.109

5 Conclusion

In this paper, we consider a tandem traffic-groomed optical network composed of N nodes linked in series, supporting alternate routing. The network is modeled as a multi-level overflow system, where each level represents a single wavelength between adjacent nodes. The queueing network is decomposed into subsystems and each subsystem is analyzed using a combination of methods developed by Nilsson et. al, Frederick and Hayward, and Basharin and Kurenkov. This method was shown to provide a good approximate analysis of large overflow systems supporting multiple traffic sources.

While this work only considers tandem networks, future work will consider the application of this analysis method to other topologies, including ring and arbitrary mesh networks.

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