Path Clustering: An Approach to Implement Absolute QoS Differentiation in Optical Burst-Switched Networks

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Abstract— **Several schemes have been proposed recently in the literature for providing absolute QoS differentiation in OBS networks, such as early drop and wavelength grouping schemes. However, these schemes only provide loss guarantees at a per-hop level. In this paper, we propose a path clustering technique to implement these per-hop schemes over an entire network. The path clustering technique provides a solution to prioritize the traffic based on hop-distances between source and destination pairs. We develop an analytical model for obtaining the optimal path clustering for a given network. By using the path clustering technique, we can improve the end-to-end loss performance of non-guaranteed traffic, and also provide absolute end-to-end loss probability of guaranteed traffic.**

I. INTRODUCTION

Optical burst switching (OBS) is a promising bufferless DWDM switching technology that can provide high wavelength utilization. OBS utilizes a signaling scheme in which an out-of-band control message is first sent to reserve resources and configure network elements along the path of the data burst. After an offset time, the data burst is transmitted all-optically through the network. One example of such a signaling scheme is just-enough-time (JET) [1].

QoS support is an important issue in OBS networks. QoS support includes delay, loss, and bandwidth guarantee. Here we focus on loss differentiation because, in OBS networks, the delay incurred from source to destination is primarily due to propagation delay, and bandwidth guarantee is implicitly provided by supporting loss guarantee.

There are two models for QoS: *relative QoS* and *absolute QoS*. In the relative QoS model, the QoS of one class is defined relatively in comparison to other classes. For example, a class of high priority is guaranteed to experience lower loss probability than a class of lower priority. However, no upper bound on the loss probability is guaranteed for the high-priority class.

Several schemes have been proposed to support the relative QoS model in OBS networks. In [2], an extra-offset-based scheme that provides relative loss differentiation was proposed. By giving a larger offset time for higher-priority class, the probability of reserving the resources for the higher-priority class burst is increased, and therefore, the loss experienced by higher-priority class traffic is decreased. In [3], QoS differentiation is provided by maintaining the number of wavelengths occupied by each class of burst. Every arriving burst is scheduled based on a usage profile maintained at every node. Arriving bursts that satisfy their usage profiles preempt scheduled bursts that do not satisfy their usage profiles, so as to maintain the preset differentiation ratio.

The absolute QoS model provides a worst-case QoS guarantee to applications. This kind of hard guarantee is essential to support applications with delay and bandwidth constraints, such as multimedia and mission-critical applications. Moreover, from the ISP's point of view, the absolute QoS model is preferred in order to ensure that each user receives an expected level of performance. Efficient admission control and resource provisioning mechanisms are needed to support the absolute QoS model.

Several schemes have been proposed in [5], [6] for providing absolute loss to the guaranteed traffic, namely, *early dropping* and *wavelength grouping*. The integration of these two schemes significantly reduces the loss experienced by the non-guaranteed traffic, while also guaranteeing the loss of the guaranteed traffic. However, these schemes only provide absolute loss at a per-hop level.

The primary objective of this paper is to implement these absolute QoS differentiation schemes over an entire network, so as to ensure that the maximum loss requirement on each hop along every path satisfies the end-to-end loss requirement. In this paper, we propose a path clustering technique that groups and prioritizes traffic based on hop-distances between source and destination pairs. By using the path clustering technique, we can improve the end-to-end loss performance of non-guaranteed traffic, and also provide absolute end-to-end loss probability of guaranteed traffic. Our schemes assume that the signaling protocol is JET [1] and the burst scheduling algorithm is LAUC [7] which schedules the bursts on channels resulting in the minimum gap.

The paper is organized as follows: Section II discusses the network architecture to support the end-to-end absolute QoS model, and describes the schemes for providing absolute loss guarantees at a per-hop level. Section III proposes a path clustering technique for providing absolute QoS differentiation over an entire network, and describes how to find an optimal path clustering. The analytical loss model for the path clustering technique is developed in Section IV. Section V studies the performance of optimal path clustering. Section VI concludes the paper.

II. ABSOLUTE QOS NETWORK ARCHITECTURE

Absolute QoS differentiation relies on proper resource provisioning and admission control. One simple resource provisioning technique is to allocate resources for the traffic of each service class based on its QoS requirements. In this technique, each service Class i is assumed to require a maximum network-wide loss guarantee, $P_{C_i}^{NET}$. Given that each OBS node main-

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tains the same loss guarantee, $P_{C_i}^{MAX}$ for Class i traffic, we can calculate the $P_{C_i}^{MAX}$ at each node from the diameter of the network, D, and $P_{C_i}^{NET}$ as follows,

$$P_{C_i}^{MAX} = 1 - e^{(ln(1-P_{C_i}^{NET}))/D}. \qquad (1)$$

Therefore, if the actual loss probability is guaranteed to be less than $P_{C_i}^{MAX}$ at each node along the path, then the network-wide loss probability $P_{C_i}^{NET}$ is guaranteed end-to-end.

In OBS networks, admission control can be implemented only at the edges nodes, since the edge nodes have the capability to electronically buffer incoming traffic and the core nodes do not have any buffers. Therefore, the maximum arrival rate between every source-destination pair can be controlled at the edge node during burst assembly. We assume that the burst arrivals in the OBS network follow a Poisson process. Based on the maximum arrival rate of the guaranteed traffic, the routing algorithm, and the network topology, we can obtain the maximum offered load of the guaranteed traffic on every link. For every link, let L_{C_i} be the maximum offered load of Class i traffic, and let W_{C_i} be the minimum number of wavelengths required in order to guarantee that the loss probability of Class i traffic is below $P_{C_i}^{MAX}$. We can compute W_{C_i} for the guaranteed traffic of Class i using the standard Erlang-B formula,

$$\frac{L_{C_i}^{W_{C_i}}/W_{C_i}!}{\sum_{x=0}^{W_{C_i}} L_{C_i}^{x}/x!} \leq P_{C_i}^{MAX}. \qquad (2)$$

Hence, in order to guarantee the maximum end-to-end loss, each core node must provide at least W_{C_i} wavelengths and must guarantee the maximum per-hop loss probability, $P_{C_i}^{MAX}$, for each Class i traffic.

There are several schemes that can guarantee the maximum per-hop loss probability, they are, *early drop by span* (EDS), *dynamic wavelength grouping* (DWG), and the integrated EDS and DWG [6]. In EDS, each node maintains an early dropping flag for each priority class other than the highest-priority class. These flags are updated periodically based on the measured and the target loss probabilities for bursts of each priority. The flags give an indication of whether or not incoming bursts of a given priority should be dropped. A flag value of 1 for a given priority indicates that incoming bursts of that priority should be dropped, while a flag value of 0 indicates that incoming bursts of that priority should not be dropped. The DWG scheme provisions the number of wavelengths for each priority class, and schedules bursts on a subset of wavelengths.

When EDS is combined with DWG, EDS does not actually drop incoming bursts based on the early dropping flags, but instead assigns a temporary label to the burst. The label is used by the DWG scheme to determine which wavelengths the burst can use. For example, a label of value $L0$ may indicate that the burst can be scheduled on any available wavelength, while a label of value $L3$ may indicate that the burst can only be scheduled on a small subset of the wavelengths. If all of the wavelengths in this subset are already occupied by other bursts labeled $L3$, then an incoming burst labeled $L3$ will be dropped. In general, if the early dropping flags are 0 for all priorities, then the EDS scheme should assign a label of $L0$ to all incoming bursts, regardless of the burst priorities. On the other hand, if the early dropping flag is 1 for a given priority i, then Priority i bursts should be assigned a label that restricts the number of wavelengths that the bursts of Priority i can use.

III. PATH CLUSTERING

In order to implement the per-hop schemes over an entire network, an approach is necessary to ensure that the combined loss probability on each hop along a path satisfies the end-to-end loss requirements. A simple technique (as described in Section II), is to have the same loss guarantee, $P_{C_i}^{MAX}$, at every hop, so that the end-to-end loss probability of the maximum hop-distance path is guaranteed. In this technique, each class of traffic would be assigned its own unique priority level. The limitation of this approach is that the loss probability experienced by bursts that are traversing shorter hop-distance paths will be much lower than the required end-to-end loss requirement. This reduced loss probability for the bursts traversing shorter hop-distance path leads to increased loss probability for the non-guaranteed traffic (higher intentional dropping).

Another simple (but extreme) technique is to set different P_{Ci}^{MAX} for each specific hop-distance path at every node. Such an approach, though optimal in performance, is not scalable. For example, if the number of different hop-distances of paths is six and the number of traffic classes is two, then the number of priority levels supported at the core nodes must be equal to seven. Class 0 traffic would have six priority levels corresponding to the six different hop-distance paths, and Class 1 traffic would have a single priority level. Hence, if a network supports multiple service classes, the scheduling at each node becomes impractical. In order to provide absolute loss guarantee over an entire network in a practical manner, we propose a *path clustering* technique, which aims to achieve a balance between the number of priority levels that needs to be maintained at each node and the amount of intentional dropping of lower-priority class bursts in the entire network.

In path clustering, the source-destination pairs are divided into different clusters based on their path hop-distance. In the following discussion, we assume that the maximum number of clusters supported in the network is two. Consider a network that has paths of hop-distance from $\{1, 2, \ldots, k\}$. For each service class i, let the per-hop loss guarantee for the maximum hop-distance path be $P_{C_i}^{MAX}$, and let a possible clustering combination be $G_{C_i}^{0} = \{\lfloor k/2 \rfloor + 1, \ldots, k\}$, and $G_{C_i}^{1} = \{1, 2, \ldots, \lfloor k/2 \rfloor\}$. Each node must maintain two different traffic statistics for each guaranteed service class i, one for each cluster. This can be achieved by assigning a unique priority to all guaranteed traffic belonging to a specific cluster. If there are n guaranteed service classes and one best effort service class, the number of priority levels required is $(2n+1)$. The traffic belonging to Cluster $G_{C_i}^{0}$ is assigned a higher priority, $(2i)$, than the traffic belonging to Cluster $G_{C_i}^{1}$, which is assigned a lower priority, $(2i + 1)$. The per-hop loss guarantee for traffic of each priority is computed based on the maximum hop-distance in the corresponding cluster using (1). Then, paths of hop-distance belonging to Cluster $G_{C_i}^{0}$, must provide a per-hop loss guarantee, $P_{P_{2i}}^{MAX}$ for priority $(2i)$ traffic, and paths of hop-distance belonging to Cluster $G_{C_i}^{1}$, must provide a per-hop loss guarantee, $P_{P_{2i+1}}^{MAX}$ for priority $(2i + 1)$ traffic. We observe that the traffic traversing paths belonging to Cluster $G^1_{C_i}$ can still satisfy the end-to-end loss guarantee, $P^{NET}_{C_i}$, with a relaxed per-hop maximum of $P^{MAX}_{P_{2i+1}}$, since this traffic traverses fewer hops.

We now describe the procedure for provisioning the required number of wavelengths for each guaranteed class of traffic, the procedure for scheduling using the integrated EDS and DWG scheme, and the procedure for finding the optimal path clustering. Without loss of generality, we consider a network with two classes of traffic that can support two clusters.

A. Provisioning Minimum Number of Wavelengths

This section describes how to provision the minimum number of wavelengths required for each guaranteed class of traffic. We need to compute the arrival rates for the guaranteed traffic on every link based on the clustering, the traffic arrival distribution, the routing algorithm, and the network topology.

Given a network with two classes of traffic, in which Class 0 traffic is guaranteed an absolute loss probability, and Class 1 is the best-effort traffic, the network must support at least three traffic priorities in order to handle two clusters. Each ingress node assigns either Priority 0 or Priority 1 to Class 0 bursts based on the clustering, and assigns Priority 2 to all Class 1 bursts.

Let us consider the following notation:

λ_{sd}: traffic arrival rate between source s and destination d.
$\lambda^{sd}_{C_0}$: arrival rate of Class 0 traffic between source s and destination d.
$\lambda^{sd}_{C_1}$: arrival rate of Class 1 traffic between source s and destination d, where $\lambda^{sd}_{C_1} = (\lambda_{sd} - \lambda^{sd}_{C_0})$.
l_{ij}: link between node i and node j.
r_{sd}: route from source s to destination d based on routing algorithm.
h_{sd}: hop-distance of route (path) r_{sd}.
$\lambda^{ij}_{P_0}$: arrival rate of Priority 0 traffic on link l_{ij}.
$\lambda^{ij}_{P_1}$: arrival rate of Priority 1 traffic on link l_{ij}.
$\lambda^{ij}_{P_2}$: arrival rate of Priority 2 traffic on link l_{ij}.

The arrival rates for the prioritized traffic on link l_{ij} are as follows,

$$\lambda^{ij}_{P_0} = \sum_{\{\forall(s,d)|l_{ij}\in r_{sd}, h_{sd}\in G^0_{C_0}\}} \lambda^{sd}_{C_0}, \tag{3}$$

$$\lambda^{ij}_{P_1} = \sum_{\{\forall(s,d)|l_{ij}\in r_{sd}, h_{sd}\in G^1_{C_0}\}} \lambda^{sd}_{C_0}, \tag{4}$$

$$\lambda^{ij}_{P_2} = \sum_{\{\forall(s,d)|l_{ij}\in r_{sd}\}} \lambda^{sd}_{C_1}. \tag{5}$$

On every link, the loss guarantee of Priority 0 traffic, $P^{MAX}_{P_0}$, and the loss guarantee of Priority 1 traffic, $P^{MAX}_{P_1}$, are computed based on (1), where D is equal to the maximum hop-distance of the cluster. The node must provision the minimum number of wavelengths, namely, W_{P_0} and W_{P_1}, for Priority 0 and Priority 1 traffic. W_{P_0} and W_{P_1} are provisioned using (2).

B. Scheduling Using Integrated EDS and DWG

This section describes the scheduling scheme in path clustering based on the integrated EDS and DWG. Table I shows the label assignment under different traffic scenarios when path clustering is implemented. The first two columns represent the early dropping flags, e_1 and e_2, for bursts of Priority 1 and Priority 2, respectively. The third, fourth, and fifth columns indicate the labels assigned to the arriving bursts of Priority 0, Priority 1, and Priority 2, respectively. Bursts of Priority 0 are always labeled $L0$. Bursts of Priority 1 are labeled $L0$ if e_1 is 0, and labeled $L1$ if e_1 is 1. Bursts of Priority 2 can be labeled $L0$, $L1$, $L2$, or $L3$ depending on the values of e_1 and e_2.

TABLE I
LABEL ASSIGNMENT.

e_1	e_2	Priority 0 Burst Label	Priority 1 Burst Label	Priority 2 Burst Label
0	0	L0	L0	L0
0	1	L0	L0	L2
1	0	L0	L1	L1
1	1	L0	L1	L3

TABLE II
WAVELENGTH PROVISIONING.

Burst Label	Arrival Rate	Max Wavelengths Scheduled On
L0	λ_{L0}	W
L1	λ_{L1}	W_{P1}
L2	λ_{L2}	$W - W_{P1}$
L3	λ_{L3}	W_{P2}

Table II gives the required number of wavelengths on which a burst with a given label can be scheduled. Let W_{P_2} be the number of wavelengths provisioned for Priority 2 traffic (non-guaranteed traffic). Since Priority 0 and Priority 1 traffic belong to the same Class 0 traffic, W_{P_2} is provisioned based on the number of wavelengths required by Class 0 traffic, that is, $W_{P_2} = W - W_{C_0}$. We allow all bursts labeled $L0$ to be scheduled on any available wavelength. All bursts labeled $L1$ are only scheduled on W_{P_1} wavelengths since we need to provide the loss guarantee of Priority 1 traffic. All bursts labeled $L2$ are scheduled on $(W - W_{P_1})$ wavelengths, since this restriction ensures that a minimum of W_{P_1} wavelengths are reserved for bursts labeled $L1$. All bursts labeled $L3$ are scheduled on W_{P_2} wavelengths.

C. Finding Optimal Path Clustering

There are two parameters that define a path clustering: the number of clusters and the elements in each cluster. The number of clusters depends on how many priority levels the network can support. The assignment of elements into each cluster determines the per-hop loss guarantee of each cluster and the arrival rates of different priority traffic. The optimal path clustering can be found offline as follows.

Let us consider a network with paths of hop-distances from one to six. Given that the network can support two clusters, the possible cluster combinations for the six hop-distance network will be {1}{2,3,4,5,6}, {1,2}{3,4,5,6}, {1,2,3}{4,5,6}, {1,2,3,4}{5,6}, and {1,2,3,4,5}{6}. For each cluster combination, we initially provision the wavelengths on every link in the network. For example, with a clustering of {1} and {2,3,4,5,6}, all Class 0 bursts along a path with a hop-distance of one will be assigned Priority 1 (low), and all Class 0 bursts along a path with a hop-distance of two, three, four, five, or six will be assigned Priority 0 (high). Each core node would satisfy two different per-hop maximum loss probabilities, $P_{P_0}^{MAX}$ and $P_{P_1}^{MAX}$. All Class 1 bursts will be assigned Priority 2. We can then compute the per-hop loss of each priority traffic using the analytical model in the following section. The end-to-end loss probability of Class 1 traffic can be obtained by re-arranging (1). This procedure is repeated for each of the cluster combinations for the six hop-distance network, {1}{2,3,4,5,6}, {1,2}{3,4,5,6}, {1,2,3}{4,5,6}, {1,2,3,4}{5,6}, and {1,2,3,4,5}{6}. The clustering with the least end-to-end loss probability of Class 1 traffic, which can also support the maximum loss probability of the guaranteed Class 0 traffic, is the optimal clustering. If the traffic is uniformly distributed among all source-destination pairs, we only need to analyze the per-hop loss performance of a bottleneck link under each cluster combination. In this case, the optimal clustering is the cluster combination with the least per-hop loss probability of Class 1 traffic.

IV. PATH CLUSTERING LOSS MODEL

In this section, we develop an analytical loss model for the path clustering technique, where the absolute QoS scheme employed at each hop is the integrated EDS and DWG scheme. Without loss of generality, we model a two-class network. The proposed model can be extended for a multi-class network.

In the model, we assume that the total burst arrival to a node is Poisson with rate λ. Given the arrival rates of Class 0 and Class 1 traffic, as well as the clustering, we calculate the individual arrival rates of every priority traffic, namely λ_{P_0}, λ_{P_1}, and λ_{P_2}. We then compute the individual arrival rates for each type of traffic with a given label according to Table III. Let $P_{P_1}^{ED}$ be the mean of $p_{P_1}^{ED}$, and $P_{P_2}^{ED}$ be the mean of $p_{P_2}^{ED}$ at steady state. The arrival rates of traffic labeled $L0$, $L1$, $L2$, $L3$ are as follows,

$$\lambda_{L0} = \lambda_{P_0} + (1-P_{P_1}^{ED})\lambda_{P_1} + (1-P_{P_1}^{ED})(1-P_{P_2}^{ED})\lambda_{P_2}, \quad (6)$$

$$\lambda_{L1} = P_{P_1}^{ED}\lambda_{P_1} + P_{P_1}^{ED}(1-P_{P_2}^{ED})\lambda_{P_2}, \quad (7)$$

$$\lambda_{L2} = (1-P_{P_1}^{ED})P_{P_2}^{ED}\lambda_{P_2}, \quad (8)$$

$$\lambda_{L3} = P_{P_1}^{ED}P_{P_2}^{ED}\lambda_{P_2}. \quad (9)$$

We assume that the bursts arrive in the same order as their burst header packets at each node. We model each link as a continuous time Markov chain with the state defined as $X = \{x_0, x_1, x_2, x_3\}$, where x_0, x_1, x_2, and x_3 are the number of wavelengths that are busy serving bursts labeled $L0$, $L1$, $L2$, and $L3$, respectively. The state transition rates are as follows,

$$q_{(x_0,x_1,x_2,x_3)(x_0-1,x_1,x_2,x_3)} = \begin{cases} x_0\,\mu & x_0 > 0 \\ 0 & \text{otherwise,} \end{cases}$$

$$q_{(x_0,x_1,x_2,x_3)(x_0,x_1-1,x_2,x_3)} = \begin{cases} x_1\,\mu & x_1 > 0 \\ 0 & \text{otherwise,} \end{cases}$$

$$q_{(x_0,x_1,x_2,x_3)(x_0,x_1,x_2-1,x_3)} = \begin{cases} x_2\,\mu & x_2 > 0 \\ 0 & \text{otherwise,} \end{cases}$$

$$q_{(x_0,x_1,x_2,x_3)(x_0,x_1,x_2,x_3-1)} = \begin{cases} x_3\,\mu & x_3 > 0 \\ 0 & \text{otherwise,} \end{cases}$$

$$q_{(x_0,x_1,x_2,x_3)(x_0+1,x_1,x_2,x_3)} = \begin{cases} \lambda_{L0} & x_0 < W \\ 0 & \text{otherwise,} \end{cases}$$

$$q_{(x_0,x_1,x_2,x_3)(x_0,x_1+1,x_2,x_3)} = \begin{cases} \lambda_{L1} & x_1 < W_{P1} \\ 0 & \text{otherwise,} \end{cases}$$

$$q_{(x_0,x_1,x_2,x_3)(x_0,x_1,x_2+1,x_3)} = \begin{cases} \lambda_{L2} & x_2 < (W - W_{P1}) \\ 0 & \text{otherwise,} \end{cases}$$

$$q_{(x_0,x_1,x_2,x_3)(x_0,x_1,x_2,x_3+1)} = \begin{cases} \lambda_{L3} & x_3 < W_{P2} \\ 0 & \text{otherwise.} \end{cases} \quad (10)$$

From the Markov chain, we can solve the steady-state probabilities $p(x_0, x_1, x_2, x_3)$. The probability that a burst labeled $L0$ is dropped by the DWG scheduler is equal to the probability that all of the wavelengths are busy. Thus, the loss probability for traffic labeled $L0$ is given by,

$$P_{L0} = \sum_{i=0}^{W_{P_1}} \sum_{j=0}^{W-W_{P_1}} \sum_{k=0}^{W_{P_2}} p(W-(i+j+k), i, j, k). \quad (11)$$

A burst with Label $L1$ is dropped either when all wavelengths are occupied, or when the number of wavelengths occupied by burst labeled $L1$ is W_{P_1}, but all of the wavelengths are not occupied. Therefore, the loss probability for traffic labeled $L1$ is as follows,

$$P_{L1} = P_{L0} + \sum_{i=0}^{W} \sum_{j=0}^{W-W_{P_1}} \sum_{k=0}^{W_{P_2}} p(i, W_{P_1}, j, k), \quad (12)$$

where $i + j + k + W_{P_1} < W$. Similarly,

$$P_{L2} = P_{L0} + \sum_{i=0}^{W} \sum_{j=0}^{W_{P_1}} \sum_{k=0}^{W_{P_2}} p(i, j, W - W_{P_1} - i - k, k), \quad (13)$$

where $j + (W - W_{P_1}) < W$, and

$$P_{L3} = P_{L0} + \sum_{i=0}^{W} \sum_{j=0}^{W_{P_1}} \sum_{k=0}^{W-W_{P_1}} p(i, j, k, W_{P_2}), \quad (14)$$

where $i + j + k + W_{P_2} < W$.

Hence, the loss probabilities of Priority 0, Priority 1, and Priority 2 bursts are given as,

$$P_{P_0} = P_{L0}, \quad (15)$$

$$P_{P_1} = P_{L0}(1 - P_{P_1}^{ED}) + P_{L1}P_{P_1}^{ED}, \quad (16)$$

and

$$P_{P_2} = P_{L0}(1 - P_{P_1}^{ED})(1 - P_{P_2}^{ED}) \; + \; P_{L1}P_{P_1}^{ED}(1 - P_{P_2}^{ED}) \\ + \; P_{L2}(1 - P_{P_1}^{ED})P_{P_2}^{ED} \; + \; P_{L3}\, P_{P_1}^{ED}P_{P_2}^{ED}. \quad (17)$$

$P_{P_1}^{ED}$ and $P_{P_2}^{ED}$ can be calculated from P_{P_0} and P_{P_1} respectively based on the EDS scheme,

$$P_{P_i}^{ED} = \begin{cases} 0 & P_{P_{i-1}} < P_{P_{i-1}}^{MIN} \\ (P_{P_{i-1}} - P_{P_{i-1}}^{MIN})/\delta_{P_{i-1}} & P_{P_{i-1}}^{MIN} \le P_{P_{i-1}} < P_{P_{i-1}}^{MAX} \\ 1 & P_{P_{i-1}} \ge P_{P_{i-1}}^{MAX}, \end{cases} \quad (18)$$

where $\delta_{P_{i-1}}$ is the early dropping span of Priority $(i-1)$ and $i \geq 1$.

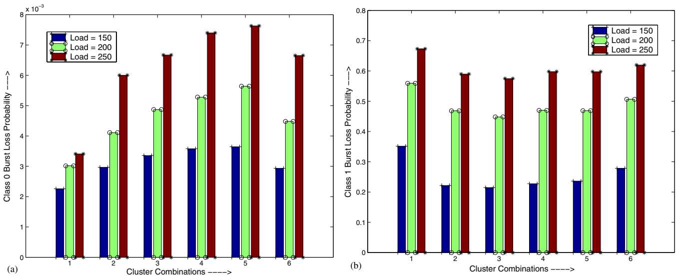

Fig. 1. (a) Class 0 and (b) Class 1 end-to-end loss probability versus different cluster combinations for the 24-node network.

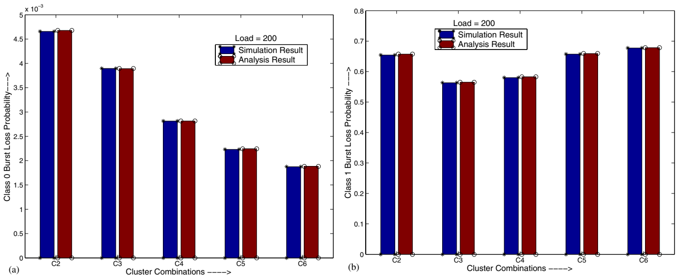

Fig. 2. (a) Class 0 and (b) Class 1 loss probability versus different cluster combinations for the bottleneck link $(9, 10)$ at a network load of 200 Erlang.

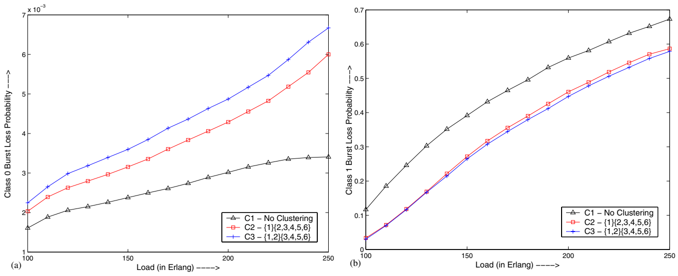

Fig. 3. (a) Class 0 and (b) Class 1 end-to-end loss probability versus load for the 24-node network.

V. NUMERICAL RESULTS

We adopt a 24-node mesh network for the network-level simulation, in which the maximum hop-distance is 6 and the number of wavelength on each link is 16. Traffic is uniformly distributed among the source-destination pairs. Fixed shortest-path routing is used. Since the maximum hop-distance in the 24-node network is 6, let $C1 = \{1,2,3,4,5,6\}$ represent the non-path clustering case, and let $C2 = \{1\}\{2,3,4,5,6\}$, $C3 = \{1,2\}\{3,4,5,6\}$, $C4 = \{1,2,3\}\{4,5,6\}$, $C5 = \{1,2,3,4\}\{5,6\}$, and $C6 = \{1,2,3,4,5\}\{6\}$ be the five possible cluster combinations. The end-to-end loss guarantee for Class 0 traffic is $P_{C_0}^{NET} = 10^{-2}$.

Figure 1 compares Class 0 and Class 1 end-to-end burst loss probabilities for different cluster combinations over an entire network at loads of 150, 200, and 250 Erlang. We observe in Fig. 1(a), that the end-to-end loss probabilities experienced by Class 0 traffic are below $P_{C_0}^{NET} = 10^{-2}$. By using clustering, we can see an increase in loss probability experienced by Class 0 traffic, as compared to the non-clustering ($C1$) case. In Fig. 1(b), the end-to-end loss probability experienced by Class 1 traffic reduces considerably with clustering. At a load of 150, 200, and 250 Erlang, we see that cluster combination $C3$ outperforms all other combinations.

Since the traffic is uniformly distributed between all source-destination pairs, we can evaluate the loss performance of each cluster combination on bottleneck link $(9, 10)$. The cluster combination which results in least loss probability of Class 1 traffic on link $(9, 10)$, is the optimal clustering. The loss performance of each cluster combination on link $(9, 10)$ can be obtained by analysis and simulation. Fig. 2 compares the simulation results and the analytical results on link $(9, 10)$ using different cluster combinations. We see that the analytical results match the simulation results. We also observe that the cluster combination, $C3$ has the least loss probability of Class 1 traffic at a load of 200 Erlang, which is confirmed by the network-wide loss result in Fig. 1(b). Hence, using the offline calculation, we can find which of the many possible clustering combinations performs the best for a given topology at a given operating load range.

Figure 3 plots Class 0 and Class 1 end-to-end burst loss probabilities versus load under the two best cluster combinations, $C2$ and $C3$, as well as the non-path clustering case (C1). We observe from Fig. 3(a) that $C1$, $C2$, and $C3$ can satisfy the end-to-end loss requirement of Class 0 traffic. However, $C1$ incurs significantly higher loss probability for Class 1 traffic compared to $C2$ and $C3$, as illustrated in Fig. 3(b). We also observe that, at loads between 100 Erlang and 250 Erlang, cluster combination $C3$ performs the best.

VI. CONCLUSION

In this paper, we proposed a path clustering technique to implement absolute QoS differentiation over an entire network. The path clustering technique prioritizes the traffic based on hop-distances between source and destination pairs so that the guaranteed traffic traversing fewer hops can satisfy the end-to-end loss requirement with a relaxed maximum loss probability at a per-hop level. This relaxed maximum loss probability reduces intentional dropping of non-guaranteed traffic, thereby improving the loss performance of the network. We also developed an analytical loss model for the proposed path clustering technique. We showed that the model is accurate when compared with the corresponding simulation results. Using the loss model, we compute the optimal clustering for a given network and verified the results with the network level simulation.

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