階層化光ネットワーク

荒木 壮一郎†, Samrat Ganguly‡, Rauf Izmailov‡,
前野 義晴†, 西岡 到†, 末村 剛彦†

†NEC ネットワーキング研究所
〒216-8555 神奈川県川崎市宮前区宮崎 4-1-1
‡C&C Research Laboratories, NEC USA, Inc.

E-mail: s-araki@cj.jp.nec.com,

あらまし 本論文では，波長や波長バンドなどの異なる粒度のパスを持つ階層化光ネットワークについて論じた。我々は，ルーティングおよびアグリゲーションについて２つのヒューリスティックアルゴリズム(online と offline)を提案し，その性能解析を行った。解析はリングトポロジを用いて行い，メトロ網を模擬したリング網と基幹網を模擬したメッシュ網の性能シミュレーションによってその効果を確認した。これらのシミュレーションにより，階層化ルーティングを用いれば online アルゴリズムで 50%，offline アルゴリズムで 70%の大幅なコスト削減が達成できることを示した。

キーワード 光ネットワーク，フォトニックネットワーク，波長多重，波長パス，波長バンドパス，経路制御，アグリゲーション，階層，光クロスコネクト

Hierarchical Optical Networks

Soichiro ARAKI†, Samrat GANGULY‡, Rauf IZMAILOV‡,
Yoshiharu MAENO†, Itaru NISHIOKA†, and Yoshihiko SUEMURA†

† Networking Research Laboratories, NEC Corporation
1-1, Miyazaki 4-chome, Miyamae-ku, Kawasaki, Kanagawa, 216-8555
‡ C&C Research Laboratories, NEC USA, Inc.

E-mail: s-araki@cj.jp.nec.com,

Abstract We consider hierarchical optical networks with different granularities of paths and their segments (wavelengths and wavebands). We propose and analyze two heuristic routing and aggregation algorithms (online and offline). The analysis is based on ring topology; its results are supported by simulations of metro (ring) and core (mesh) networks. The simulations demonstrate a significant cost reduction (from 50% in online algorithm to almost 70% in offline one).

Key words optical network, wavelength division multiplexing, wavelength path, waveband path, routing, aggregation, hierarchy, optical cross-connect.

1. Introduction

The continuing increase of data traffic keeps the pressure on the backbone telecommunication networks. In order to satisfy the growing bandwidth demands, more diverse and more intelligent allocation of capacity is required. Optical networking has become a key technology to accommodating the rapidly expanding Internet traffic. New networks are expected to support the increasing network load by employing sophisticated transmission (wavelength division multiplexing division (WDM)) and switching (optical switches and cross-connects) technologies [1]. These advanced technologies pose various challenges that need to be addressed.

In IP networks, performance and scalability concerns called for layered mechanisms providing various levels of traffic aggregation supported by DiffServ [2] and MPLS standards [3]. In case of the optical networking, the same cost and scalability concerns translate into creation of multiple switching granularities, such as wavelengths and wavebands [4]. The optical paths thus form a mixed hierarchy in which higher-layer paths (waveband) consist of several segments of lower layer paths (wavelengths). The potential cost benefits of wavelength aggregation into wavebands was demonstrated in [5]. A waveband path occupies only two (input and output) ports of an optical switch in a node. The path hierarchy reduces node costs since a waveband can be switched optically as a single unit, thus reducing the number of expensive OEO ports required for processing individual wavelengths.

Cost-efficient implementation of optical hierarchy has to be delivered by appropriately designed routing and scheduling algorithms. Routing and wavelength assignment algorithms were extensively studied in the general context of optical networking (see [1] and its references). The hierarchy of wavelengths and wavebands can be cast in several models posing new routing and scheduling challenges.

In this paper, we propose routing and path-aggregation algorithms and analyze their performance by measuring the total cost of the ports used in the optical network.

The rest of the paper is organized in the following manner. In the next section, we describe the main elements of hierarchical optical networking and present two heuristic waveband routing and aggregation algorithms. Section 3 describes our general simulations framework. In Section 4, we present the results and discuss their implications for design and performance of waveband routing algorithms. Finally, in Section 5, we address the scope of our future work.

2. Hierarchical nodes and networks

In a hierarchical optical network, some segments (a segment is set of consecutive links) of wavelength paths can be aggregated into a waveband path at one node and disaggregated into wavelength paths at another node. The nodes participating in the aggregation and disaggregation have to be equipped with both a waveband (transparent optical) and a wavelength (opaque OEO) switch. The general structure of such a node (referred to as "hybrid cross-connect") is shown in Figure 1. A wavelength path input to the wavelength switch can be either directly routed to a neighbor node (flow *A*) or aggregated into a waveband path which is then routed to a neighbor node via a waveband switch (flow *B*). The waveband switch provides lower-cost switching that does not depend on bit-rate and waveband size. The resulting hierarchy of wavelengths and wavebands is a mixed one: logical wavebands coexist on the same fiber with individual wavelengths, providing better efficiency.

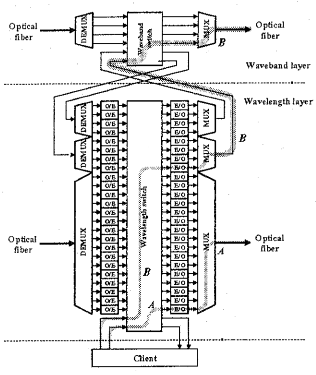

Figure 1: Hybrid cross-connect.

In this paper, we assume that the source node of a wavelength path (or the centralized server) computes only a route for the wavelength path using a wavelength-layer routing protocol that does not advertise the status of waveband resources. The coarser layer waveband path that accommodates segments of the wavelength path is computed independently, using the waveband-layer's own routing protocol or local decisions of individual nodes. Online route computation is carried out during the call setup time, while offline computation is used on a slower time scale for more efficient utilization of network resources. Since path setup requests are not frequent, the offline computation is a useful tool for network management.

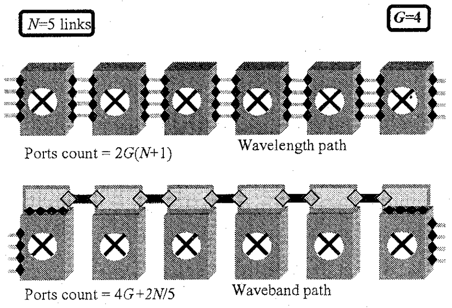

Figure 2: Routing metric: ports count.

We assume that some of the wavelengths can be aggregated into wavebands consisting of G wavelengths each. Each waveband consists of contiguous wavelengths, i.e. the waveband number m contains all the wavelengths with numbers from $(m-1)G+1$ to mG.

We define the cost of routing in hierarchical optical network as the total cost of the ports (both OEO and optical ones) required for routing the traffic flows (we assume an optical port costs five times less than an OEO port, which is unit of cost). Thus the cost of a wavelength segment consisting of N links is equal to $2G(N+1)$, while the cost of a waveband segment aggregating this wavelength segment is equal to $4G+2N/5$. Figure 2 illustrates the cost computation for a wavelength segment consisting of $N=5$ links and granularity $G=4$.

The online algorithm works in the following way. First, a wavelength path along the shortest (in terms of hop count) route from the source node to the destination node is created. Then, for each of the segments of the created wavelength path between two hierarchical nodes (starting from the longest segments and finishing at the shortest segments, consisting of two links), the following operation is executed. If the number of wavelength paths running through the entire segment is equal to G, a waveband path is created at that segment. The order of segments analyzed by the algorithm (longest segments first) facilitates the creation of longest wavebands: they provide the largest reduction of cost.

The offline algorithm works in the following way. First, all the wavelength paths are routed without any waveband aggregation. Then, starting from a large value *MaxHops* (equal to the number of hops in the longest path) the algorithm tries to locate a common segment of length *MaxHops* belonging to G wavelength paths. If such a segment is found, the corresponding waveband is created and the search is continued until no such segments could be found. In the subsequent steps, the parameter *MaxHops* is decreased by 1 and the procedure is repeated until *MaxHops* reaches the minimum value of 2.

Since the most cost benefit is created by longest wavebands, the offline algorithm attempts (as online algorithm) to maximize the cost benefits by locating the longest possible waveband paths first. The difference between two algorithms is in number of wavelength paths analyzed at each of their steps: online algorithm analyzes only the segments of the most recently created path, while the offline algorithm analyzes all wavelengths paths in the network. Both algorithms have manageable complexity for realistic networks.

3. Waveband routing simulations

In order to analyze various routing and aggregation scenarios for hierarchical waveband switching and routing, a specialized simulator was implemented. The key output of the simulator is the amount of reduction of the total cost (we call it "aggregation benefit") obtained by aggregating some segments of wavelength paths into waveband ones. As shown in Figure 2, the aggregation benefit of aggregating G parallel wavelengths paths consisting of N links (with cost $2G(N+1)$) into a waveband segment (with cost $4G+2N/5$) is equal to $1-2G(1+N)/(4G+2N/5)$.

We simulated waveband granularities from $G=2$ to $G=20$. We assumed that each link of the network could carry 160 wavelengths. The wavelengths could be aggregated into wavebands consisting of G wavelengths each, so the granularity G determines the maximum number $160/G$ of wavebands on a link.

We simulated several types of networks (see Figure 3): rings (from 10 to 60 nodes), square grids (from 16 to 81 nodes), European and American optical networks (consisting of 139 nodes) described in [4]. All simulated networks were assumed to be homogeneous: every node was able to perform waveband aggregation.

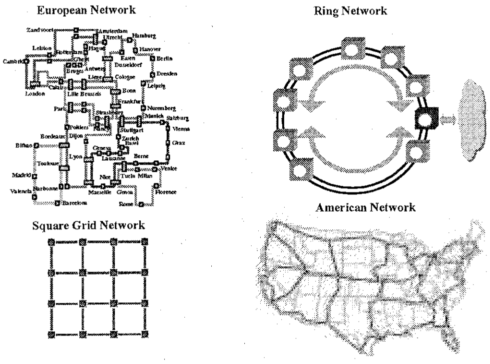

Figure 3: Simulated networks.

The traffic matrices were created to reflect skewed traffic distribution (Zipf distribution [6]) observed in real networks (for example, in distribution of Web traffic among popular sites): the nodes in the network were randomly ranked and the amount of traffic generated by a node was inversely proportional to its rank.. All wavelength and waveband paths were assumed to be uni-directional.

The traffic matrices were scaled appropriately to simulate various loads in the networks. The load was defined as the ratio of the minimum amount of bandwidth required to accommodate all the traffic flows to the total amount of bandwidth available in the network. In order to concentrate of waveband aggregation, we assumed that all the nodes have infinite number of ports. We also assumed that the nodes could convert any wavelength into any other wavelength.

4. Simulation results and discussions

We analyze the performance of waveband aggregation using a simple model of a metro ring. We assume that the ring consists of $2M+1$ nodes, one of which functions as a hub, receiving and sending traffic to all other nodes. We also assume that each node of the ring establishes the same number L of wavelength paths (so L is the load parameter) to the hub node.

The aggregation benefit reaches its maximum

$$A_{\max} = \frac{(M+6/5)L + 1/5 - 2\sqrt{LM/5}}{(M+3)L}$$

for the optimum waveband size $G_{\max} = \sqrt{LM/5}$.

Figure 4 shows the behavior of A for various G and L (for M=20). This figure and the obtained formulas for A, $A_{\max}$ and $G_{\max}$ provide several insights into performance of waveband aggregation.

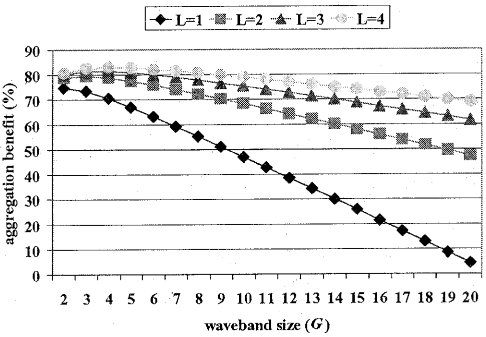

Figure 4: Aggregation benefit for M=20.

As granularity G increases to $G_{\max}$, the aggregation benefit first increases and then falls off. The optimal granularity $G_{\max}$ slowly increases with the load L (it is proportional to $\sqrt{L}$). It also slowly increases with the size (equal to $2M$+1) of the ring (it is proportional to $\sqrt{M}$). For example, for rings containing 10,20,30,40,50 and 60 nodes, where each node sends L=6 wavebands to the hub, the optimal waveband sizes $G_{\max}$ are 5, 8, 9, 11, 12 and 13, respectively. If the load L increases, the maximum benefit $A_{\max}$ converges to its maximum value $(M+6/5)/(M+3)$. For example, for rings containing 10,20,30,40,50 and 60 nodes this maximum potential aggregation benefits are 37%, 62%, 72%, 78%, 82% and 85%, respectively.

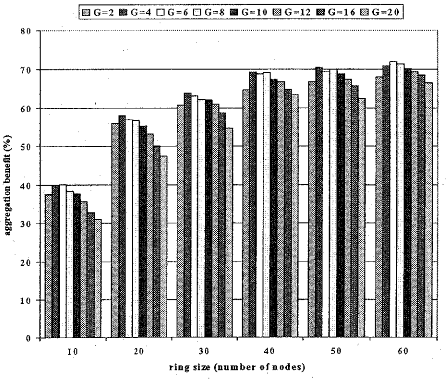

Figure 5: Ring networks: offline algorithm.

In order to compare our analytical results with simulations, we measured the performance of the offline algorithm for various rings. The traffic load of all the rings was maintained at the level of 90%. The results of our simulations are illustrated in Figure 5.

The results of simulations exhibit the behavior observed in the analytical model (which covers only hub-directed traffic flows, while our simulations cover more general Zipf distribution). As granularity G increases to some $G_{\max}$, the aggregation benefit first increases and then falls off. The optimal granularity $G_{\max}$ increases from 10 to 16 with the size of the ring (the model predicted increase from 5 to 13). As the ring size increases, the maximum benefit $A_{\max}$ increases approximately proportionally to the predicted value $(M-2)/(M+3)$, while remaining approximately 30% smaller than that of obtained by simulations.

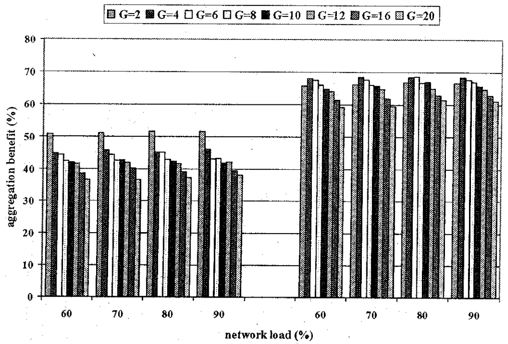

Figure 6: American optical network, online (left) and offline (right) routing.

The simulation results for American optical network under different loads (60%, 70%, 80% and 90%) are shown in Figure 6. In the simulated scenarios, the maximum aggregation benefit barely increases with the network load. Compared with ring networks, the range of optimal granularity $G_{\max}$ is smaller: it increases from 8 to 10 as the load increases. The obtained results also demonstrate the superior performance of the offline algorithms. The online algorithm delivers the maximum aggregation benefit of about 52%, while the offline algorithm can achieve more than 68% benefit.

As the network size increases (compare also the aggregation benefit values for ring network with those of larger American network), the value of aggregation benefit increases (due to the creation of longer wavebands).

Simulations for other networks and traffic patterns (not shown here) support the qualitative observations made for American network.

5. Conclusions

We studied routing models and algorithms for hierarchical optical networking. We defined routing cost of wavelengths and wavebands as ports count and proposed two routing and path-aggregation algorithms (online and offline). We proposed analytical method for analyzing the performance of waveband routing for ring networks and verified its results by extensive simulations on diverse large size networks. The results demonstrate the cost efficiency of waveband aggregation (up to 60% reduction for large networks and appropriately selected waveband granularity).

We plan to address more networks and traffic scenarios in our future work. We also plan to utilize our routing simulator for designing and testing other waveband routing algorithms for other scenarios (including integrated routing and heterogeneous networks) and more realistic assumptions of costs of OEO and optical ports.

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