Hierarchical Traffic Grooming in WDM Networks

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Upcoming Book

Traffic Grooming for Optical Networks

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Editors

Foundations and Techniques

Springer
Outline

- Motivation and problem definition
- Complexity results and implications
- Hierarchical grooming in rings
- Hierarchical grooming for general topology networks
  - clustering and hub selection
  - logical topology design and traffic routing
  - RWA
- Results and discussion
Optical Networking Trends

- Increasing data rates
  
  **OC-48** (2.5 Gbps) → **OC-768** (40 Gbps) and 100 GbE

- Increasing fiber capacity
  
  Dense WDM → 100s of λs per fiber

- Improving fiber technology
  
  Optical signals may travel longer without regeneration (OEO)

- Improving OXC technology
  
  Higher port counts, faster configuration times
Optical Network Design Considerations

- Fine traffic granularity
  Most traffic demands are sub-wavelength in magnitude

- High cost of OEO components
  Cost scales faster than linearly with the number of ports

- Optical bypass of intermediate nodes has benefits:
  - most traffic travels more than 200 Km
  - most links shorter than 200 Km
What is traffic grooming?

Efficiently set up lightpaths and groom (i.e., pack/unpack, switch, route, etc.) low-speed traffic onto high capacity wavelengths so as to minimize network resources.

Requires MUX/DEMUX and ADM/OADM devices.

But: involves much more than simple multiplexing techniques.
Traffic Grooming as Optimization Problem

- **Inputs to the problem:**
  - physical network topology (fiber layout)
  - traffic matrix $T = [t_{sd}] \rightarrow$ int multiples of unit rate (e.g., OC-3)

- **Output:**
  - logical topology
  - lightpath routing and wavelength assignment (RWA)
  - traffic grooming on lightpaths

- **Objectives:**
  - minimize total # of OEO ports in the network ($\leftrightarrow$ # of lightpaths)
  - limit the number of required wavelengths
Traffic Grooming Subproblems

1. Logical topology design - determine the lightpaths to be established.
2. Lightpath routing - route the lightpaths over the physical topology.
3. Wavelength assignment - assign wavelengths to lightpaths without clash.
Traffic Grooming Subproblems

Logical topology design → determine the lightpaths to be established
Traffic Grooming Subproblems

- **Logical topology design** → determine the lightpaths to be established
- **Lightpath routing** → route the lightpaths over the physical topology
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- **Wavelength assignment** → assign wavelengths to lightpaths w/o clash
- **Traffic grooming** → route traffic on virtual topology
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Problem Complexity

- Optimization problem:
  - can be formulated as integer linear problem (ILP)
  - is NP-hard in general → ILP solvable for toy networks only

- Difficulty arises due to RWA subproblem:
  - solvable in polynomial time for path (linear) and star networks
  - NP-hard for other topologies (including rings and trees)

- But what about the traffic grooming subproblem?
Problem instance:

- unidirectional linear (path) network
- logical topology and RWA is given
- traffic either bifurcated or not bifurcated

Objective: find a grooming of traffic onto the lightpaths

Result: problem is NP-complete \( \rightarrow \) reduction from \textit{Subset Sums}
Implications

The problem is not simplified by assuming

- fixed routing
- large numbers of wavelengths
- full wavelength conversion
Traffic Grooming in Stars

- **Switching and grooming:** only at **hub**
- **Two types of lightpaths**
  - **1-hop:** to/from the hub
  - **2-hop:** optically bypass the hub
RWA subproblem solvable in polynomial time

But: the grooming subproblem is NP-Complete

Greedy heuristic:
  - obtain an all-electronic solution → 1-hop lightpaths only
  - greedily reroute large demands onto direct (2-hop) lightpaths
  - $O(WN^2)$ running time

Experiments show good performance
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Hierarchical Grooming in Rings

- [Gerstel 2000]: single-hub, double-hub architectures, etc.
- [Chen 2005]: ring embeddings
- [Simmons 1999]: super-node architecture
- [Dutta 2002]: generalized hub architecture
Ring Embeddings

Diagram showing a ring network with access nodes and backbone nodes. The diagram indicates access wavelengths and backbone wavelengths.
Super-Node Architecture

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Hierarchical Traffic Grooming in WDM Networks
Approaches

1. Solve the ILP directly

2. Apply classical optimization tools to solve the ILP suboptimally
   - LP-relaxation techniques
   - meta-heuristics (simulated annealing, genetic algorithms)

3. Apply decomposition methods
Airline Analogy

Seattle, WA

Chicago, IL

Los Angeles, CA

Raleigh, NC

Miami, FL
Airline Traffic Analogy (2)
1. Clustering and hub selection

2. Logical topology design and traffic routing
   - **reduction:** set up direct and direct-to-hub lightpaths
   - **intra-cluster grooming:** 1st level virtual stars
   - **inter-cluster grooming:** 2nd level virtual star

3. Lightpath routing and wavelength assignment (RWA)
   - existing LFAP algorithm [Siregar et al, 2003]
Illustration: Clustering
Illustration: Reduction
Illustration: Reduction
Illustration: Intra-Cluster Grooming
Illustration: Intra-Cluster Grooming
Illustration: Intra-Cluster Grooming
Illustration: Intra-Cluster Grooming
Benefits of Hierarchical Design

- Hierarchical control and management
- RWA on physical topology relatively independent of logical topology design
- Only hubs have grooming capability
- Efficient handling of small traffic components
- Limited number of electronic hops
Clustering and Hub Selection

- Widely studied problem in network design and other domains
- Many algorithms exist, but do not address grooming considerations
- $K$-Center problem → good match
  - minimizes max distance from any node to nearest center
  - does not take into account:
    - traffic matrix
    - nodal degrees
Grooming considerations for clustering:

- Effect of number of clusters on hub size and cost objectives
- Composition of each cluster → group nodes with dense traffic
- Effect of cut links connecting to other clusters
- Physical shape of each cluster → avoid linear topology
- Selection of hubs → prefer high degree nodes
The “Virtual” Star Concept

Any arbitrary topology
The “Virtual” Star Concept

Any arbitrary topology

View as star to determine logical topology / traffic routing
The “Virtual” Star Concept

- Any arbitrary topology
- View as star to determine logical topology / traffic routing
- Star topology not used for RWA
The “Virtual” Star Concept

- Any arbitrary topology
- View as star to determine logical topology / traffic routing
- Star topology not used for RWA
- Perform RWA on original topology
Computational Considerations

- Running time complexity:
  1. Clustering: $O(N^4)$
  2. Logical topology design and traffic routing: $O(WN^2)$
  3. RWA: $O(WN^2M)$

- Algorithm scales well to large networks
  - a few seconds for 128-node network
  - permits “what-if” analysis
Lower Bounds

For evaluating algorithm effectiveness

Lightpath lower bounds:
- nodal aggregate traffic demands
- ILP relaxation

Wavelength lower bound:
- bisection of physical topology forms cut of size $k$ with traffic $t$
  going through $\rightarrow$ bound $= \frac{t}{kC}$
- used METIS tool to generate good cut

Bounds independent of grooming method
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Results: 32-Node Network, Locality Traffic

![Graph showing no. of lightpaths vs problem instance for different clusters and lower bounds.](image)

![Graph showing no. of required wavelengths vs problem instance for different clusters and lower bounds.](image)
Results: 32-Node Network, Random Traffic

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## Results: 32-Node Network, Random Traffic

<table>
<thead>
<tr>
<th>#Clusters</th>
<th>Avg LP Length</th>
<th>Avg Max Hub Degree</th>
<th>Wavelengths</th>
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<tbody>
<tr>
<td>1</td>
<td>3.17</td>
<td>266</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>3.07</td>
<td>228</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>2.93</td>
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<td>59</td>
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<tr>
<td>8</td>
<td>2.84</td>
<td>143</td>
<td>56</td>
</tr>
</tbody>
</table>
Results: 47-Node Network, Locality Traffic

Hierarchical Traffic Grooming in WDM Networks
Results: 128-Node Network, Rising Traffic
Conclusions

- Hierarchical grooming framework is effective for the objectives
- Star logical topology design applied to two levels of hierarchy
- Clustering algorithm addresses grooming considerations
- Topologies of more than 100 nodes handled easily
- Open issues:
  - integrating RWA
  - logical topologies other than star at each level
  - dynamic hierarchical grooming
  - waveband grooming