Hierarchical Traffic Grooming in WDM Networks

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Upcoming Book

Traffic Grooming for Optical Networks

Foundations and Techniques

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Optical Networks
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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
  \textbf{OC-48} (2.5 Gbps) $\rightarrow$ \textbf{OC-768} (40 Gbps) and 100 GbE

- Increasing fiber capacity
  \textit{Dense WDM} $\rightarrow$ 100s of $\lambda$s per fiber

- Improving fiber technology
  Optical signals may \textit{travel longer} without regeneration (OEO)

- Improving OXC technology
  Higher port counts, \textit{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.
Inputs to the problem:

- physical network topology (fiber layout)
- traffic matrix \( T = [t_{sd}] \rightarrow \text{int multiples of unit rate (e.g., OC-3)} \)

Output:

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

Objectives:

- minimize total # of OEO ports in the network (↔ # of lightpaths)
- limit the number of required wavelengths
Traffic Grooming Subproblems

Logical topology design
- determine the lightpaths to be established

Lightpath routing
- route the lightpaths over the physical topology

Wavelength assignment
- assign wavelengths to lightpaths w/o clash

Traffic grooming
- route traffic on virtual topology

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Traffic Grooming Subproblems

- **Logical topology design** → determine the lightpaths to be established
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Lightpath routing → route the lightpaths over the physical topology
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 w/o clash
Traffic Grooming Subproblems

- **Logical topology design** → determine the lightpaths to be established
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- **Wavelength assignment** → assign wavelengths to lightpaths w/o clash
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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 → reduction from Subset Sums
The problem is not simplified by assuming

- fixed routing
- large numbers of wavelengths
- full wavelength conversion
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 \( \rightarrow \) 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

access nodes

backbone

wavelengths

access wavelengths

backbone wavelengths

backbone nodes

access nodes
Super-Node Architecture

- Supernode 1
- Supernode 2
- Supernode 3
- Supernode 4
Generalized Hub Architecture

(a) (b)
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Grooming in General Topology 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  →  Miami, FL

Los Angeles, CA  →  Raleigh, NC
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: Clustering
Illustration: Intra-Cluster Grooming
Illustration: Intra-Cluster Grooming
Illustration: Inter-Cluster Grooming
Illustration: Inter-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 $\rightarrow$ 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
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 and discussion
Results: 32-Node Network, Locality Traffic

![Graph showing network traffic results with different clusters and problem instances.]
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>
</tr>
</thead>
<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>
<td>183</td>
<td>59</td>
</tr>
<tr>
<td>8</td>
<td>2.84</td>
<td>143</td>
<td>56</td>
</tr>
</tbody>
</table>
Results: 47-Node Network, Locality Traffic

Problem Instance

K-Center, 4 clusters
K-Center, 6 clusters
MeshClustering, 3.52 clusters
MeshClustering, 5.45 clusters

Normalized lightpath count

Normalized wavelength requirements

Problem Instance
Results: 128-Node Network, Rising Traffic

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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