

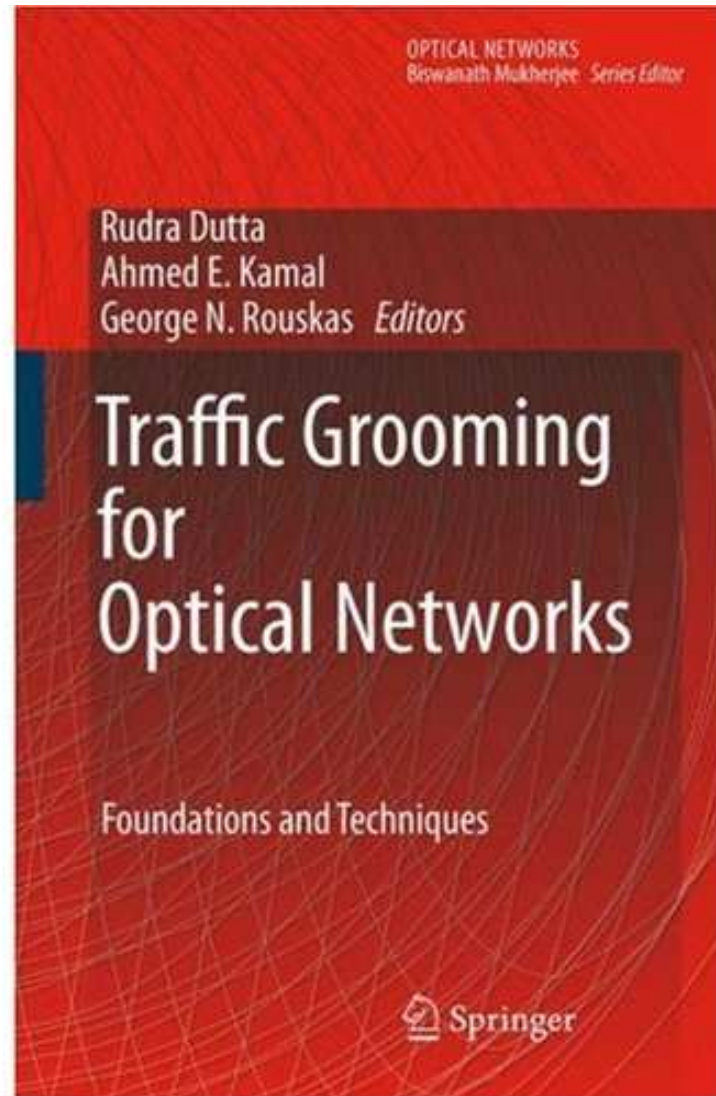
Hierarchical Traffic Grooming in WDM Networks

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Upcoming Book



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 λ s 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

Traffic Grooming in WDM Networks

- 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)

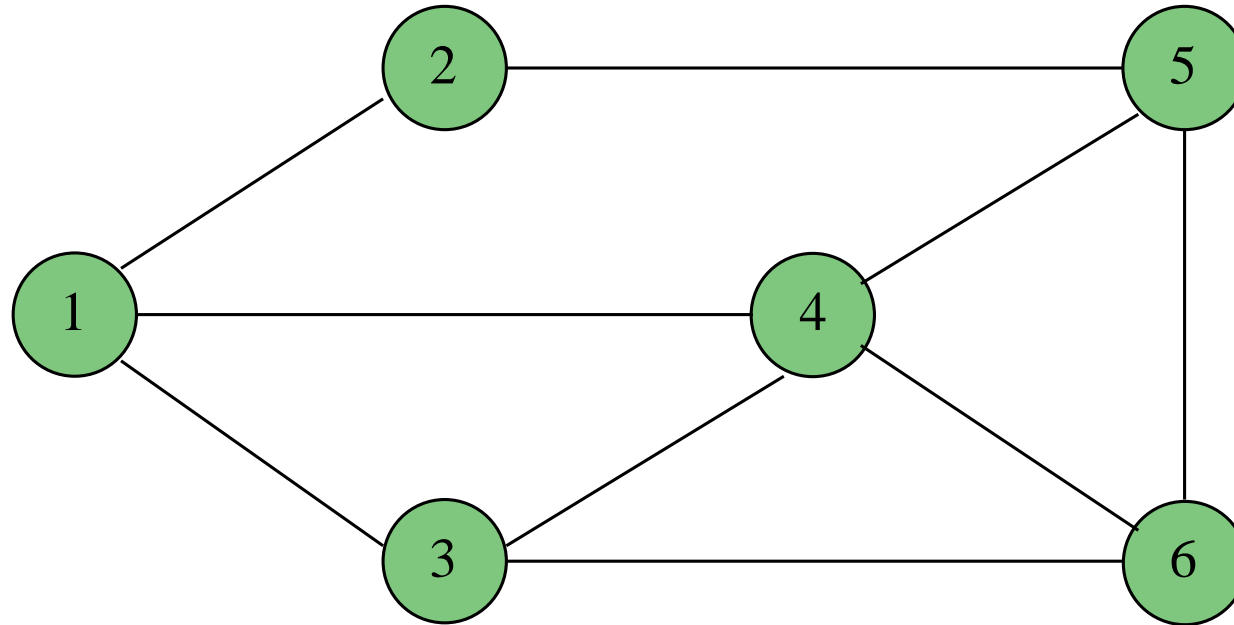
Output:

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

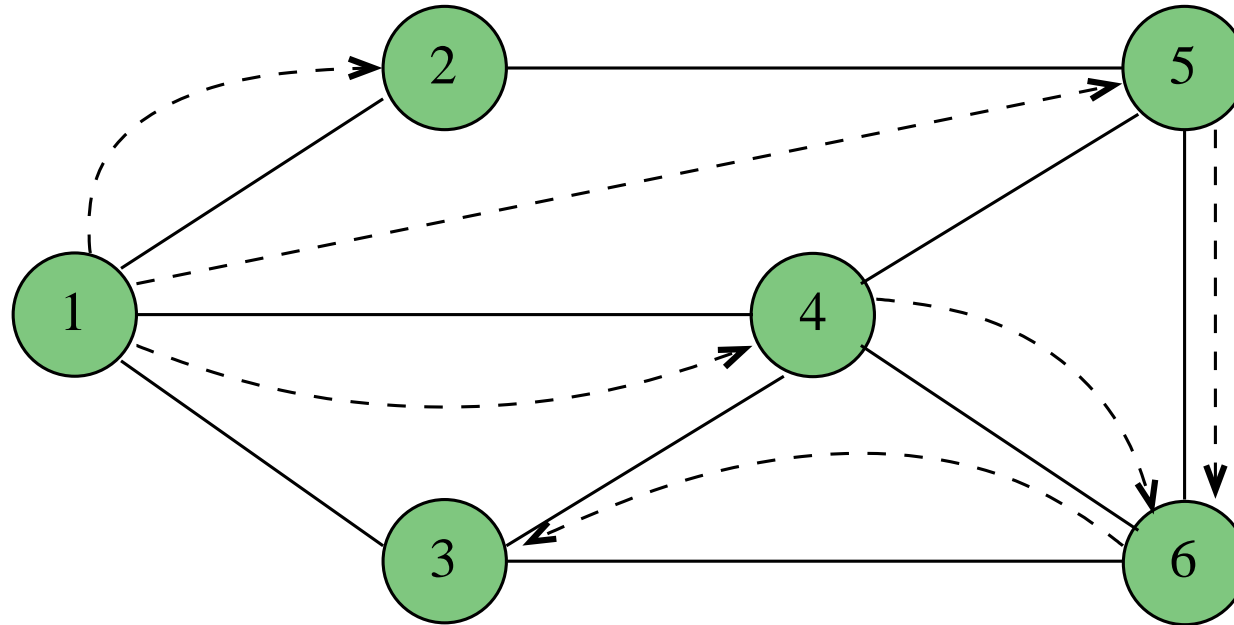
Objectives:

- minimize total # of OEO ports in the network (\leftrightarrow # of lightpaths)
- limit the number of required wavelengths

Traffic Grooming Subproblems

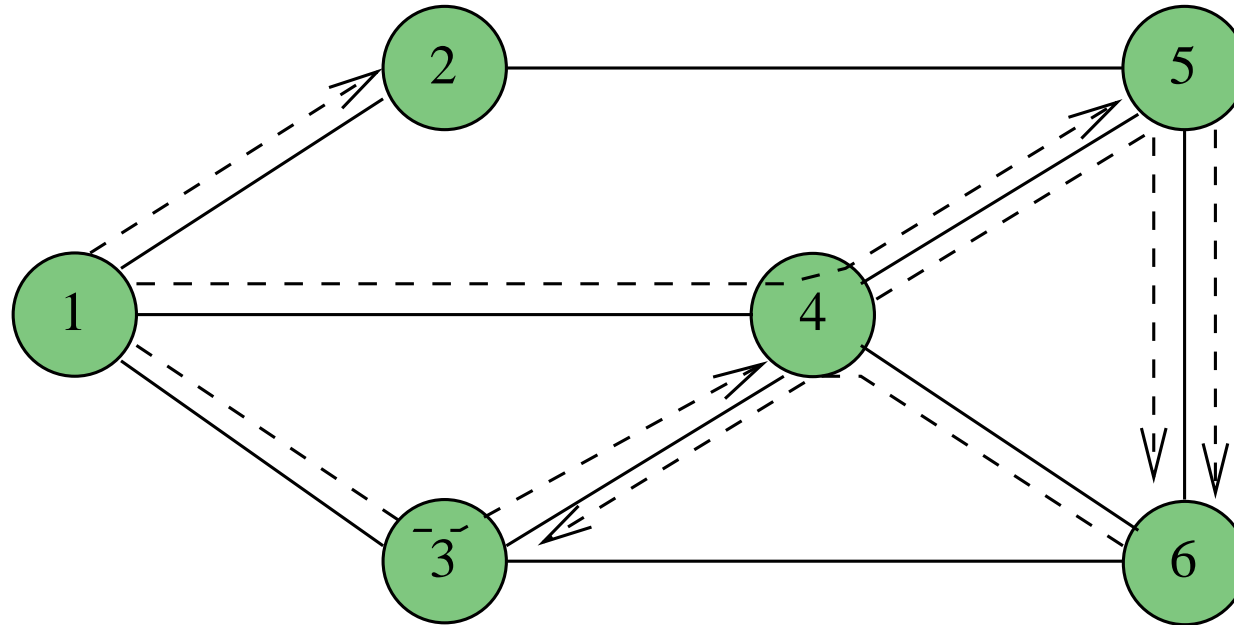


Traffic Grooming Subproblems



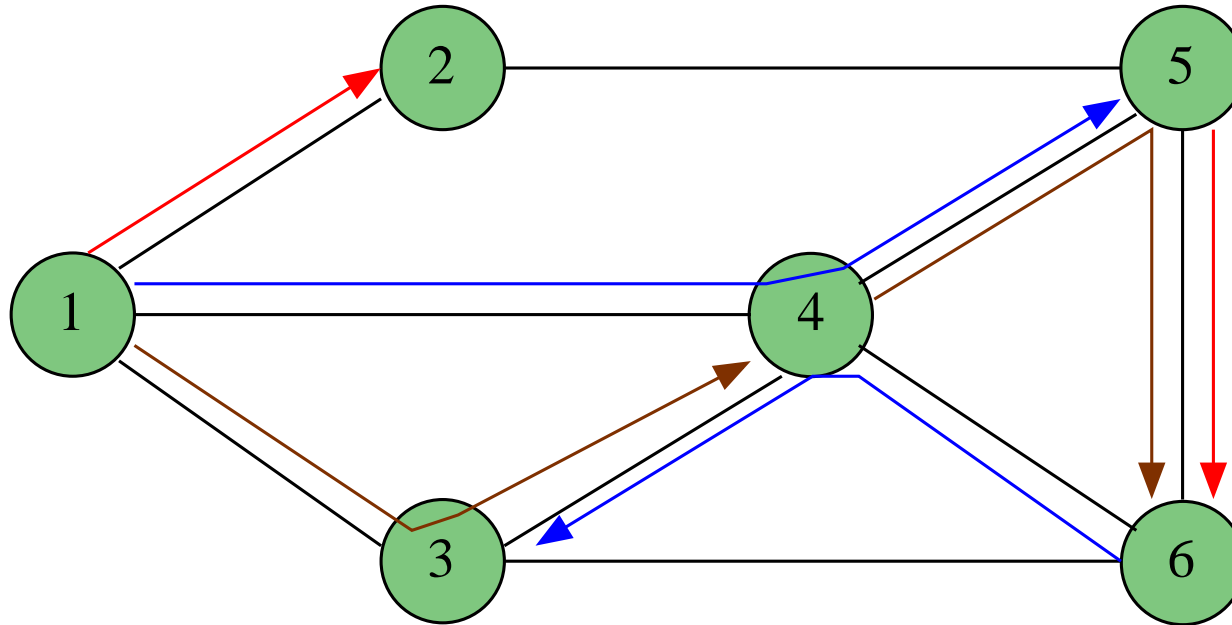
- **Logical topology design** → determine the lightpaths to be established

Traffic Grooming Subproblems



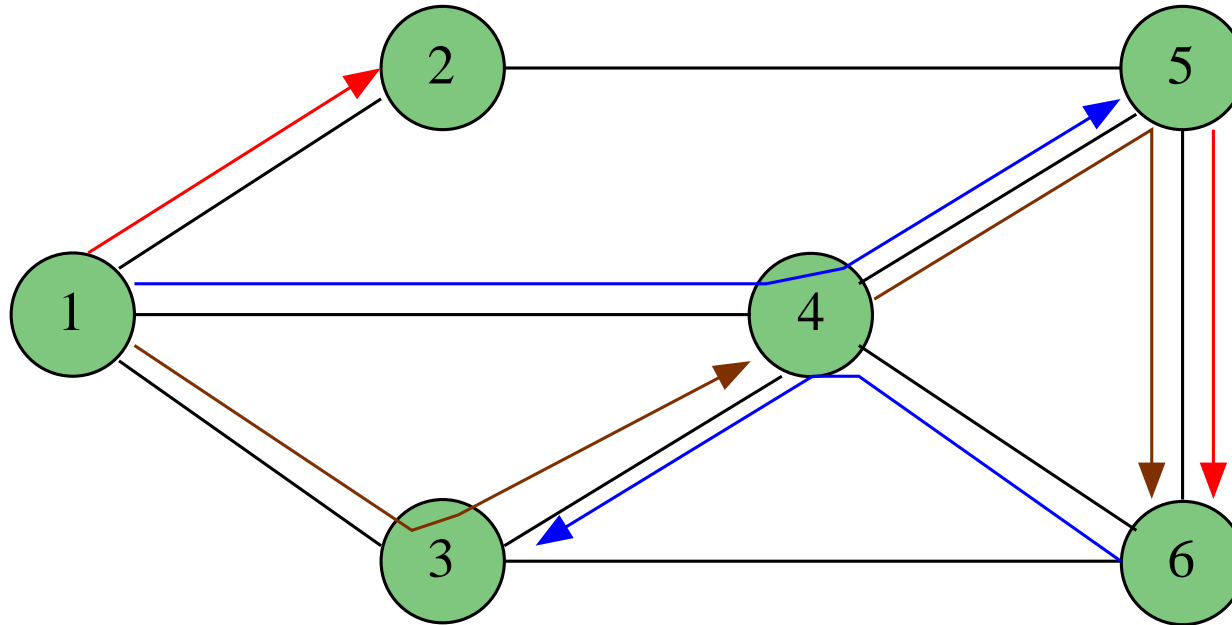
- **Logical topology design** → determine the lightpaths to be established
- **Lightpath routing** → route the lightpaths over the physical topology

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 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

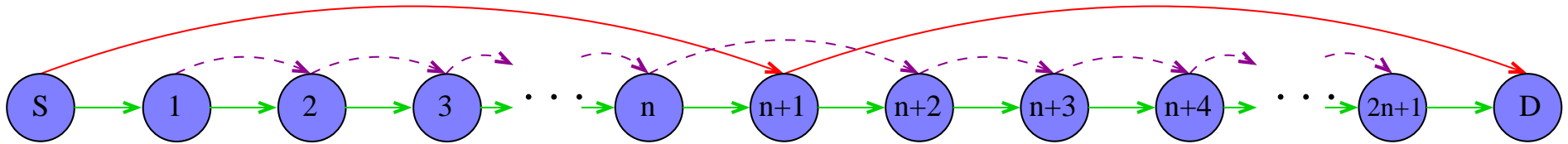
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Problem Complexity

- 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?

Traffic Grooming Complexity [JSAC 2006]



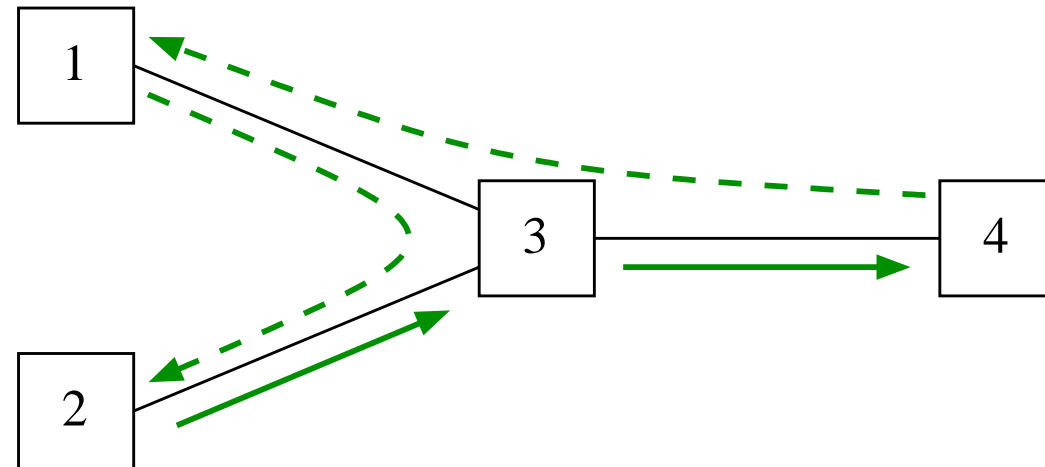
- **Problem instance:**
 - unidirectional linear (path) network
 - logical topology and RWA is given
 - traffic either bifurcated or not bifurcated
- **Objective:** find a grooming of traffic onto the lightpaths
- **Result:** problem is NP-complete \rightarrow reduction from *Subset Sums*

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

Star Grooming Complexity [JSAC 2006]

- 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

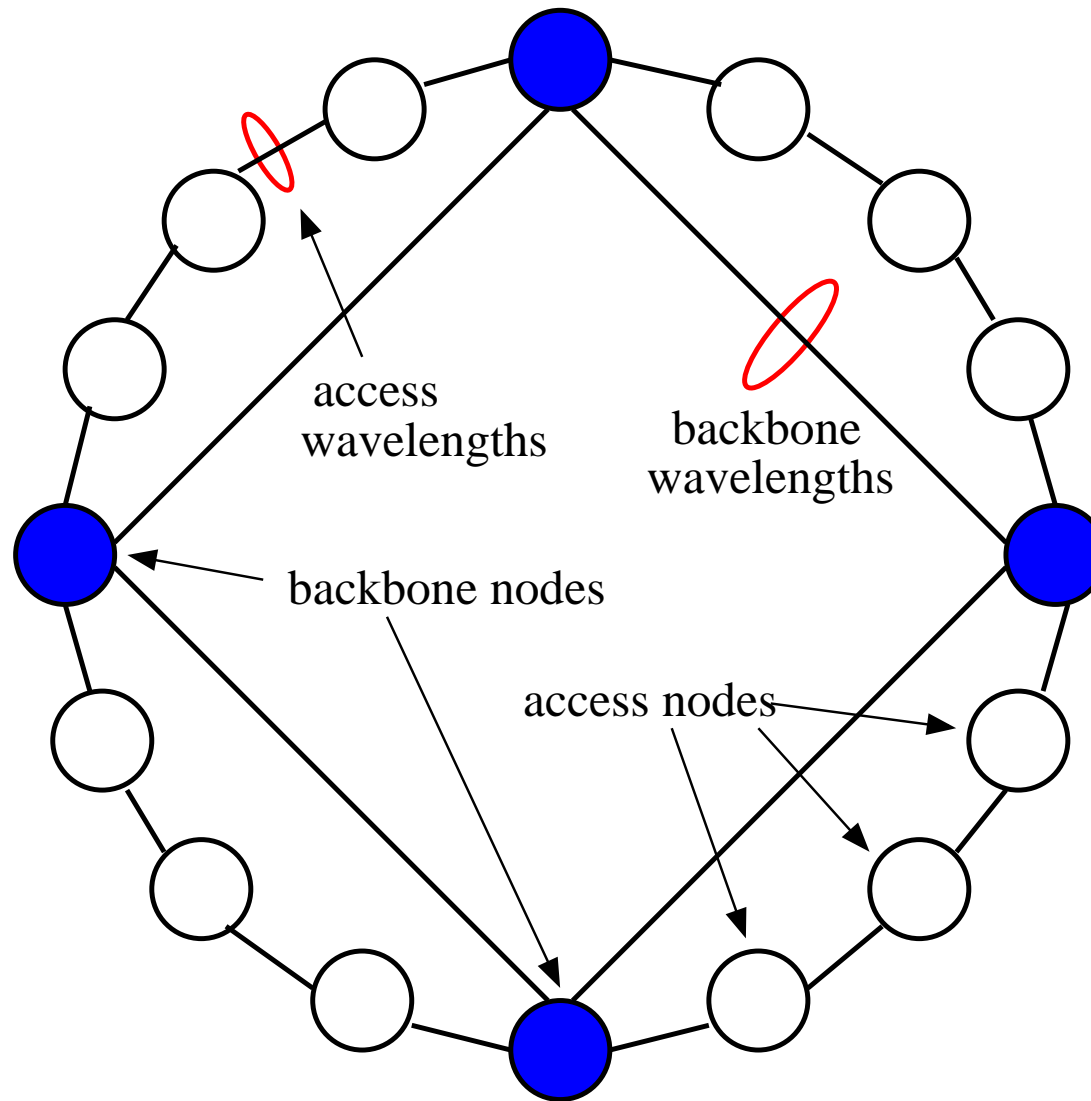
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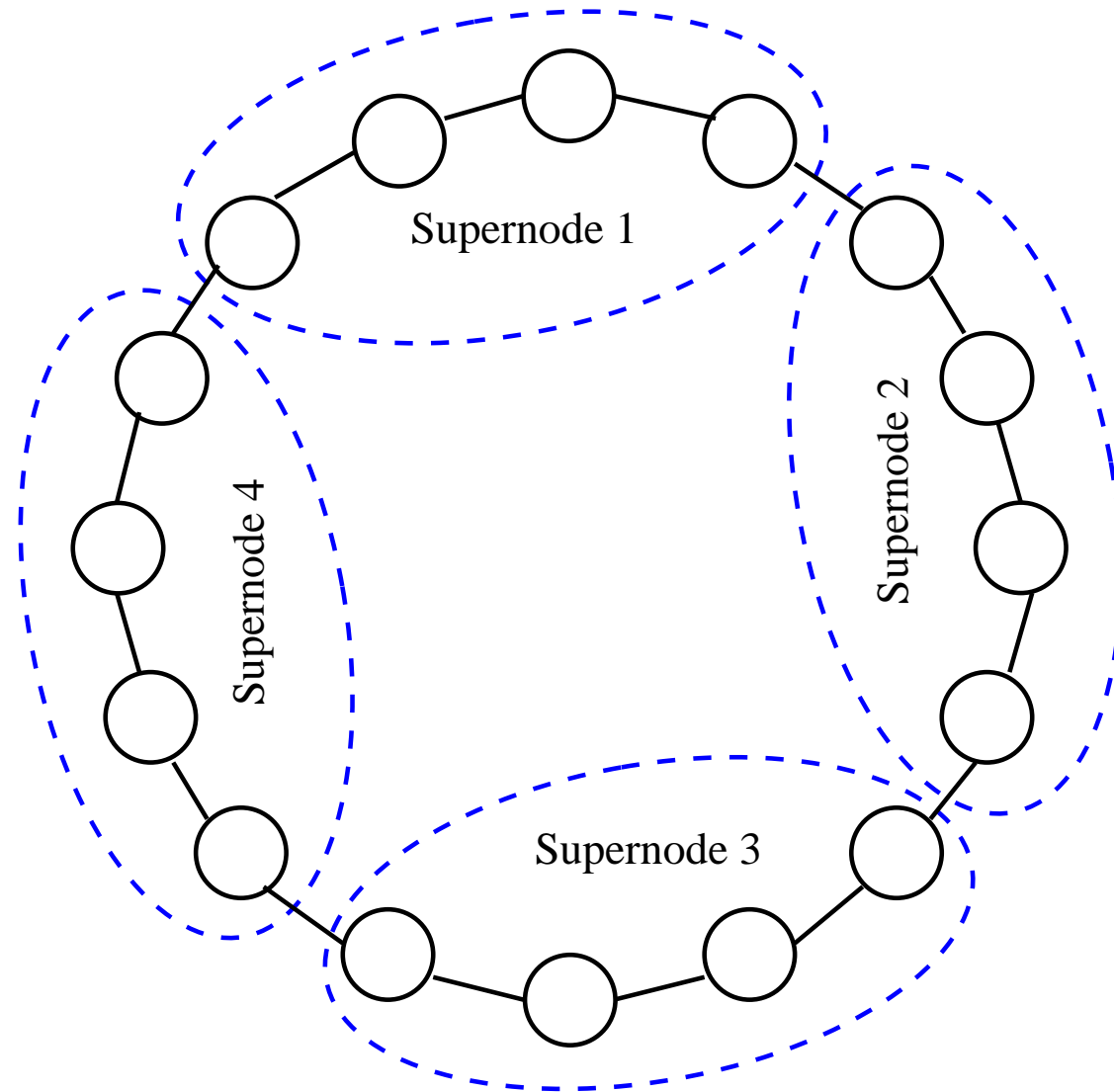
Hierarchical Grooming in Rings

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

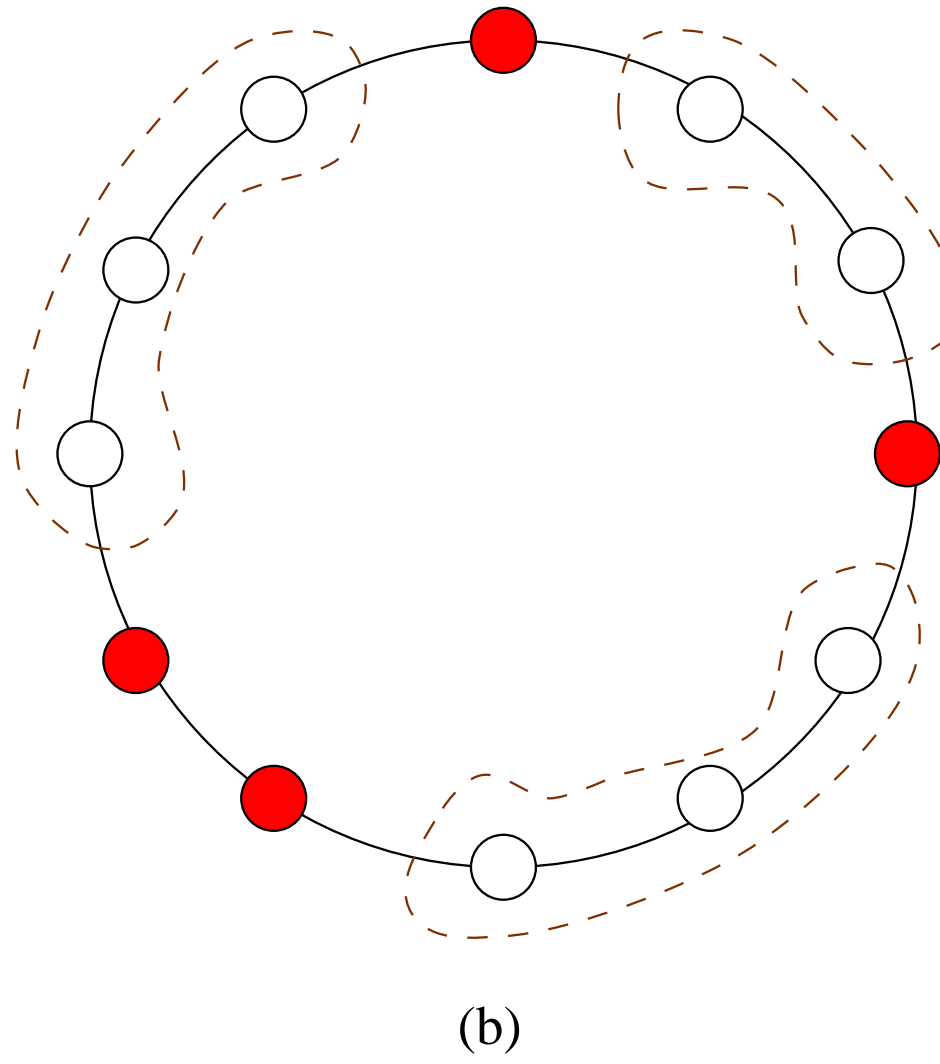
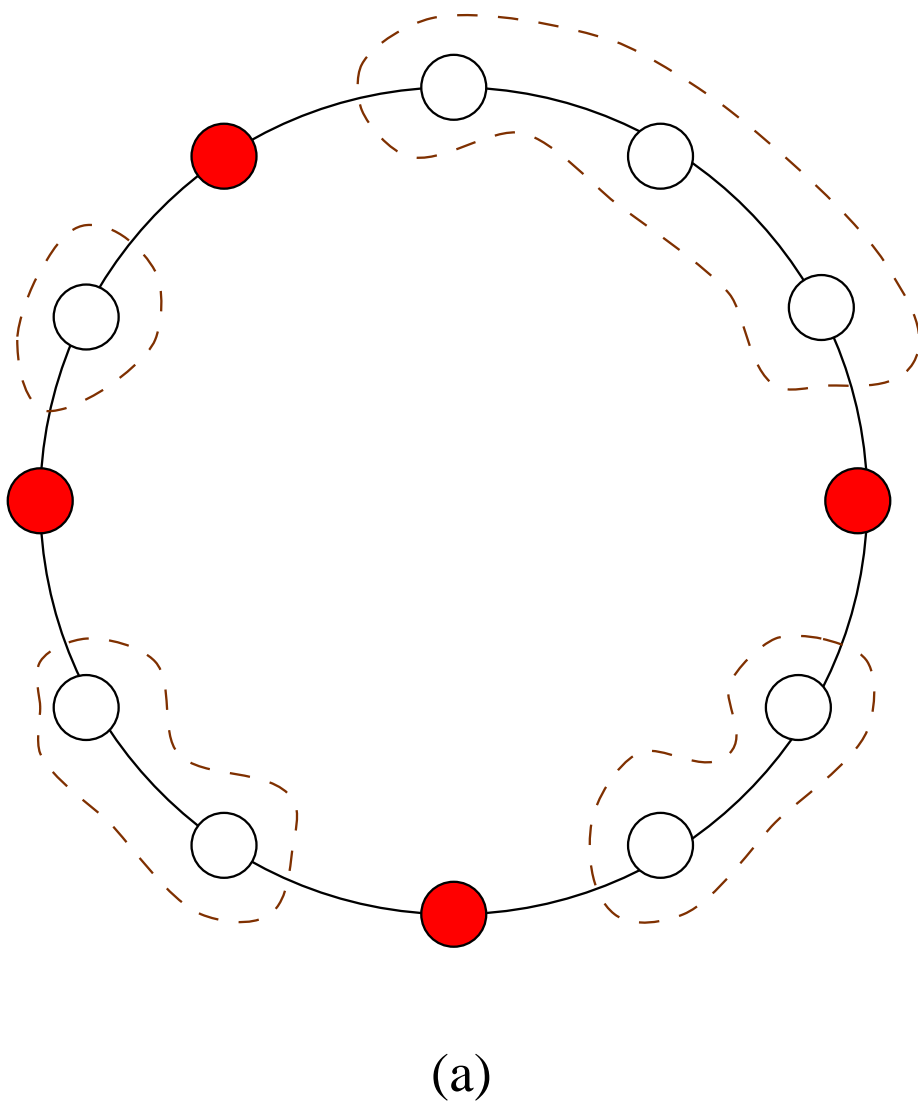
Ring Embeddings



Super-Node Architecture



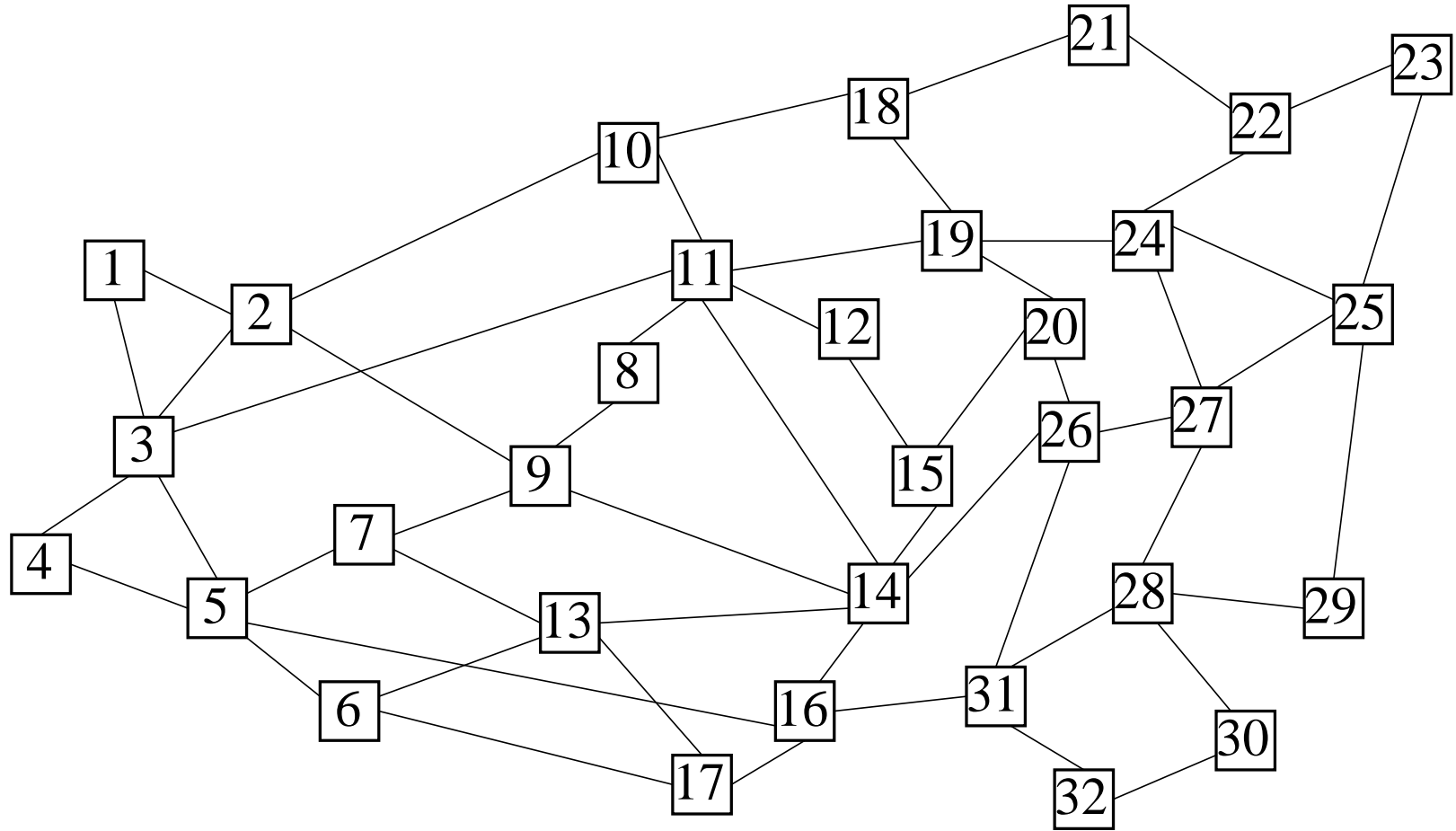
Generalized Hub Architecture



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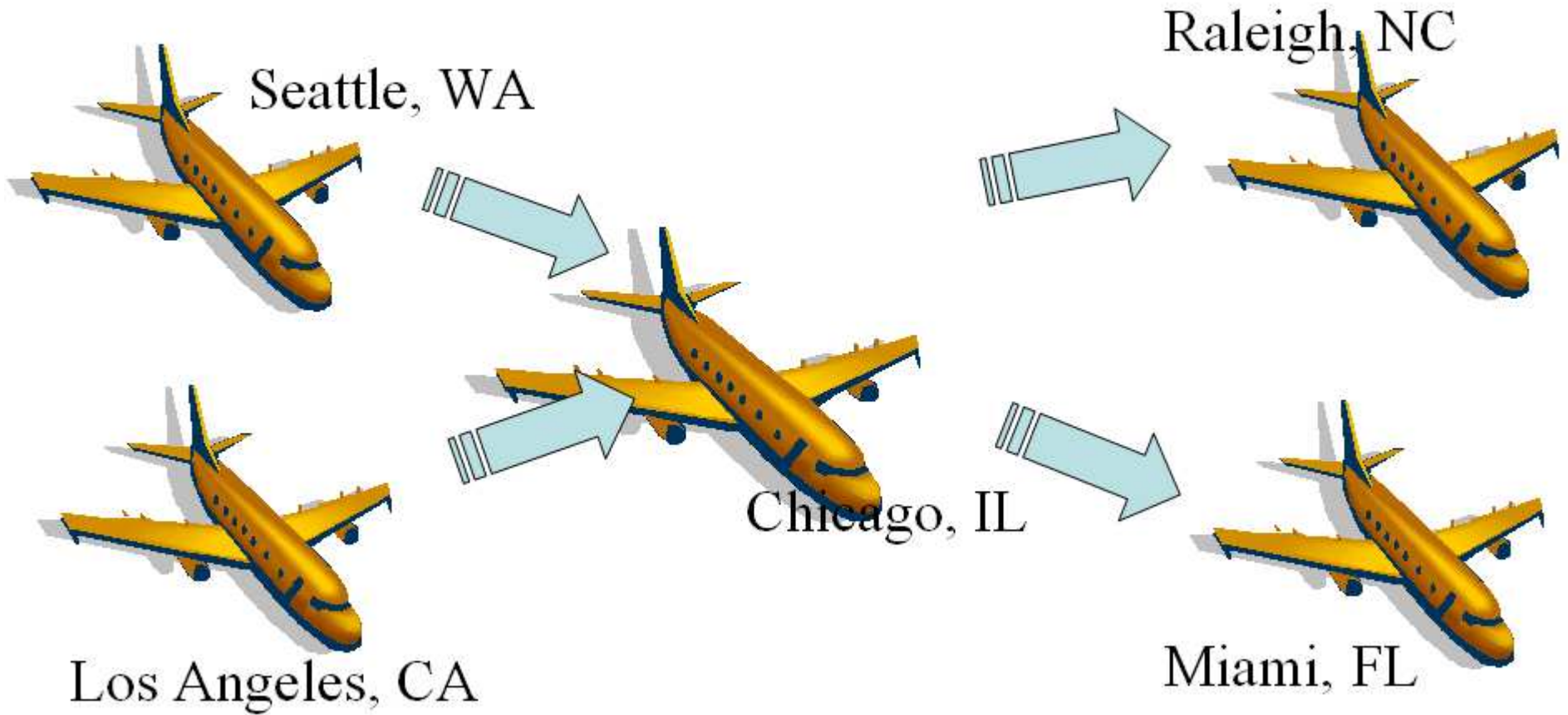
Grooming in General Topology Networks



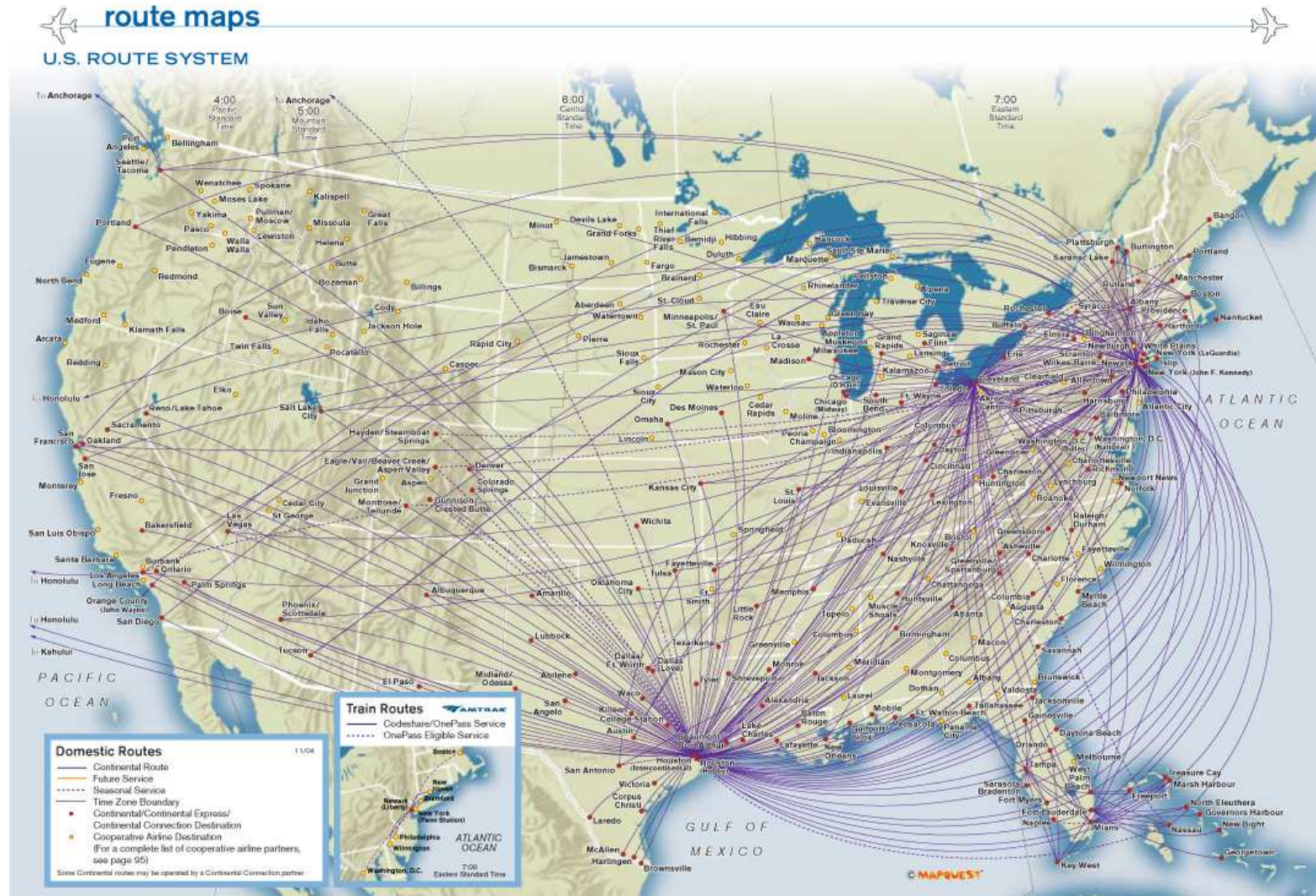
Approaches

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



Airline Traffic Analogy (2)



Hierarchical Grooming Phases [ToN 2008]

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

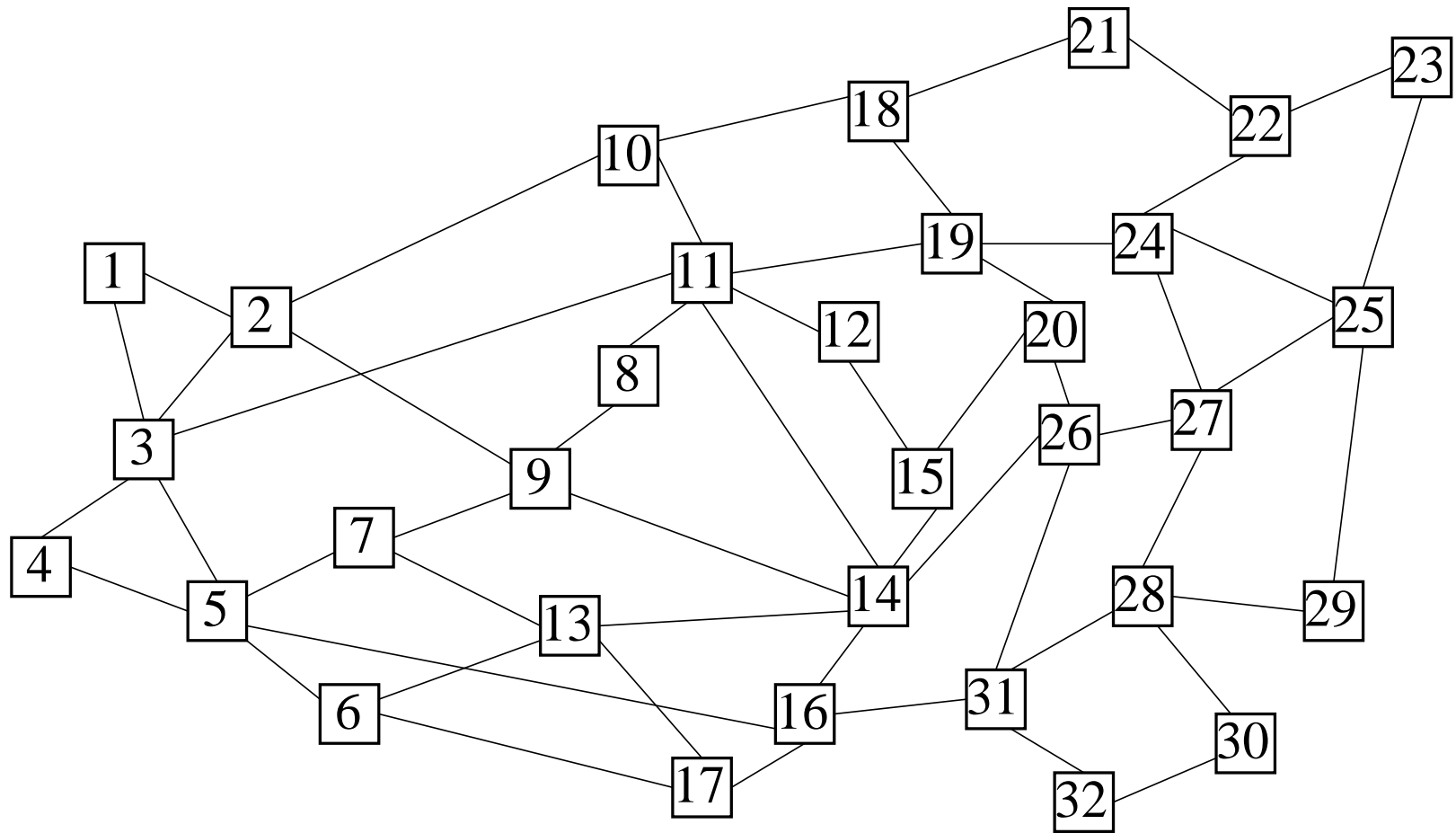


Illustration: Clustering

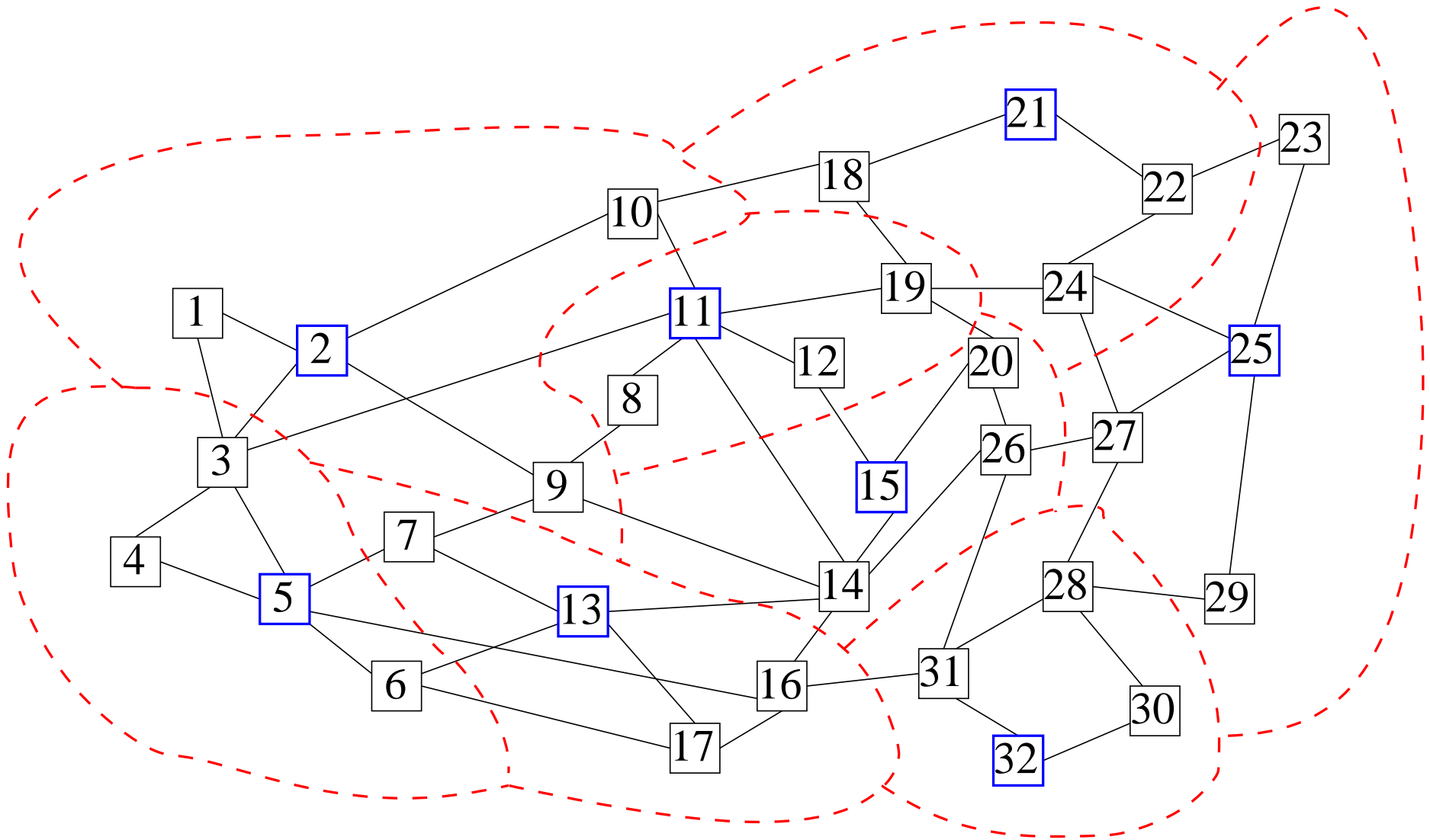


Illustration: Reduction

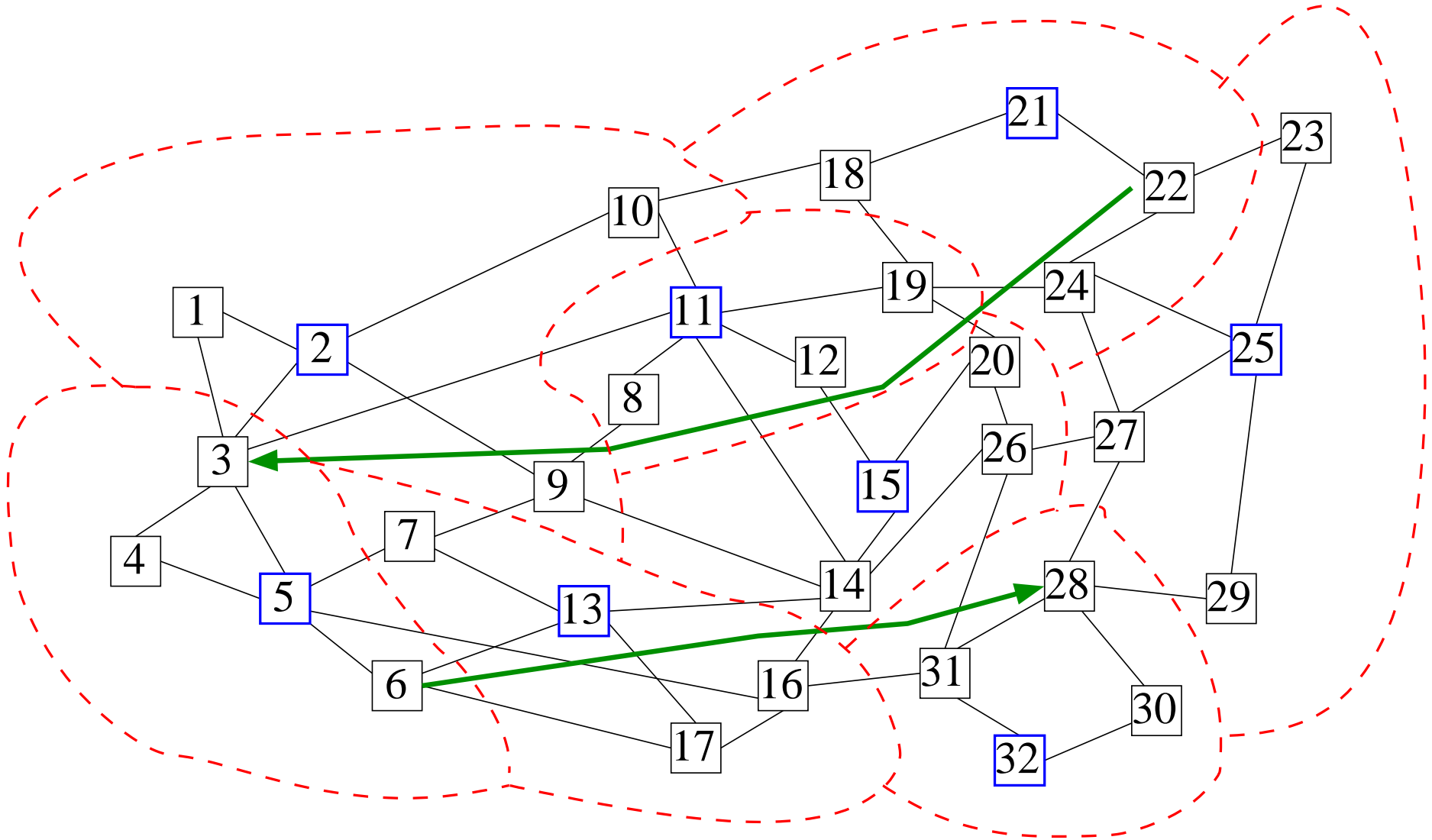


Illustration: Reduction

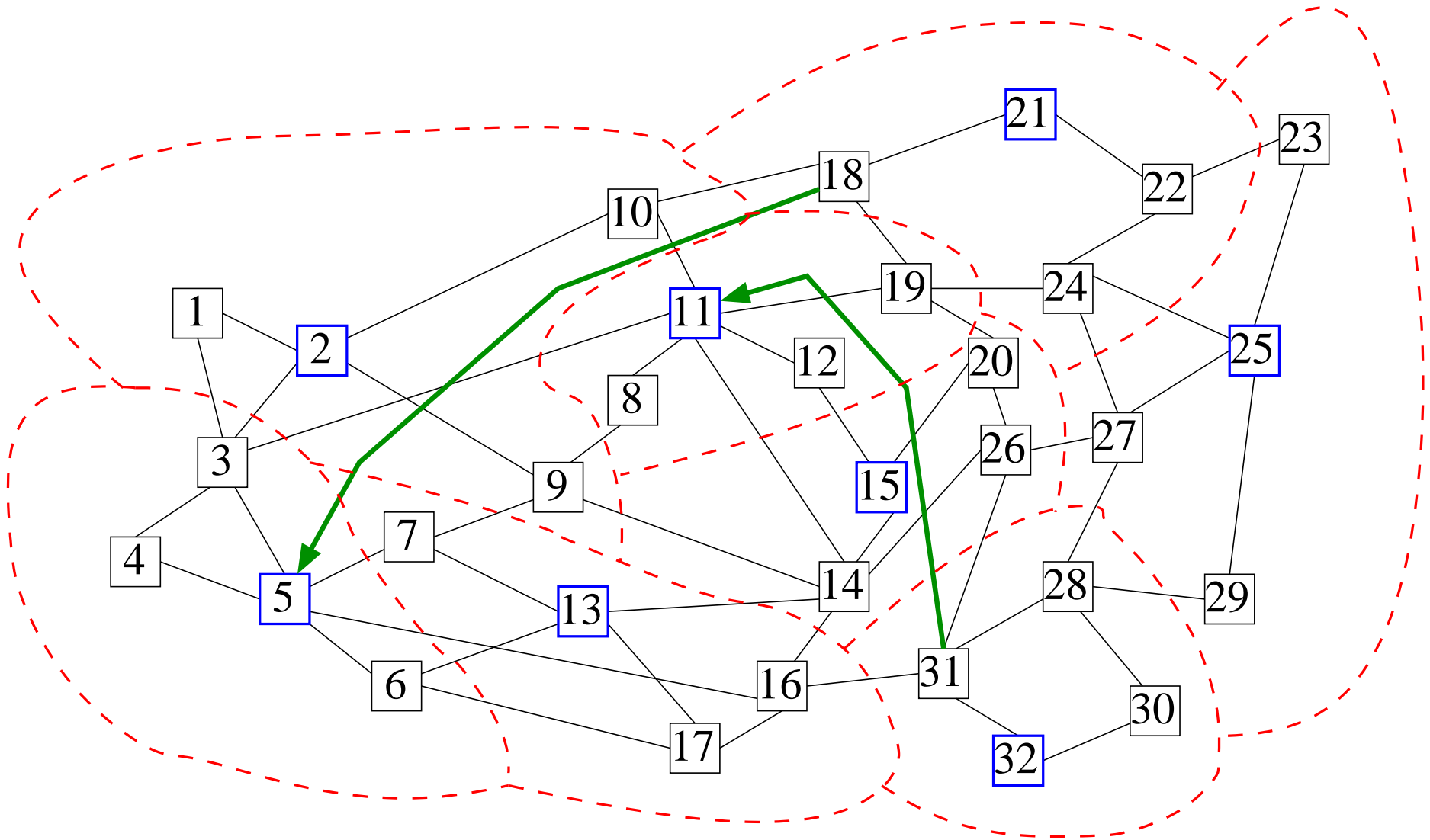


Illustration: Intra-Cluster Grooming

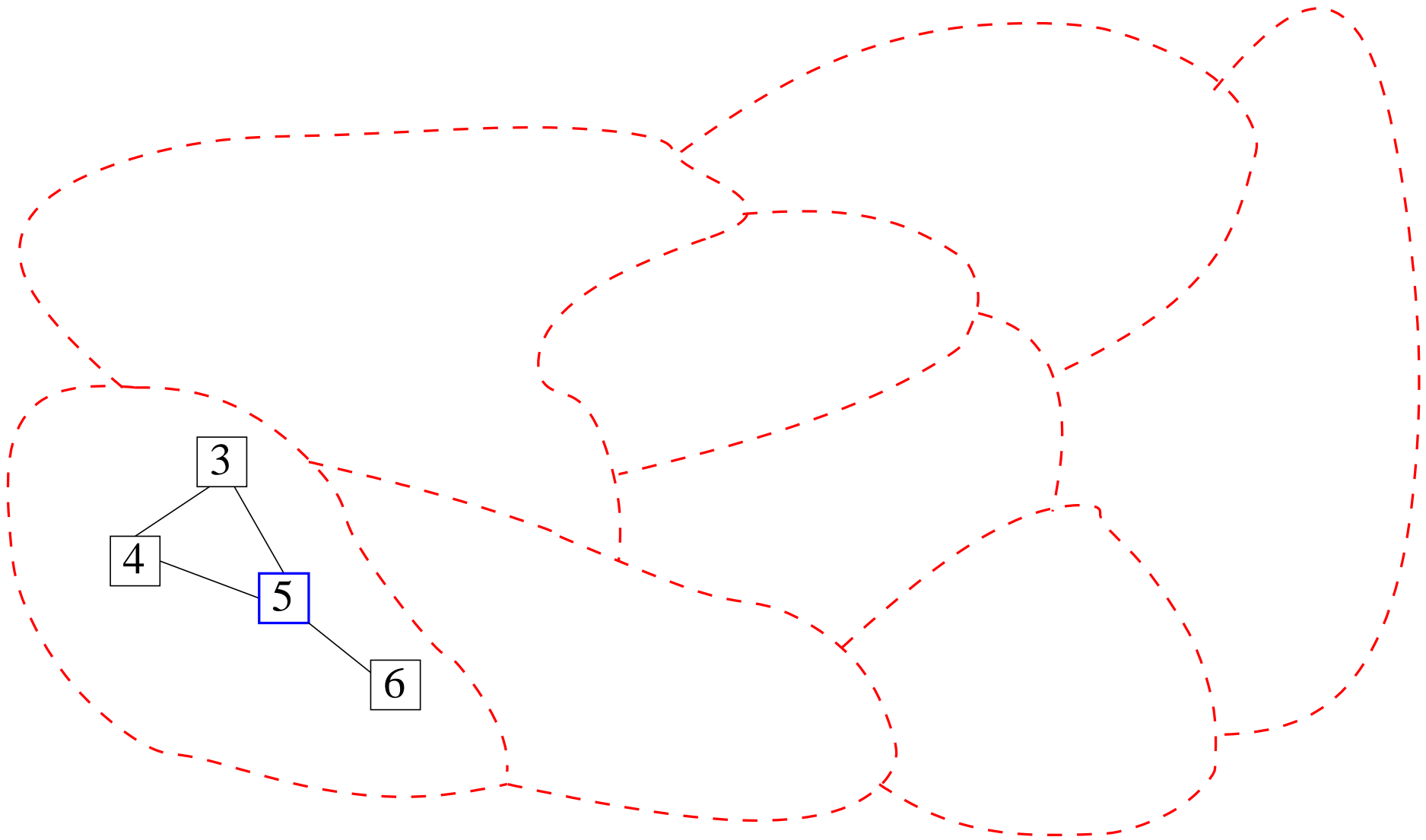


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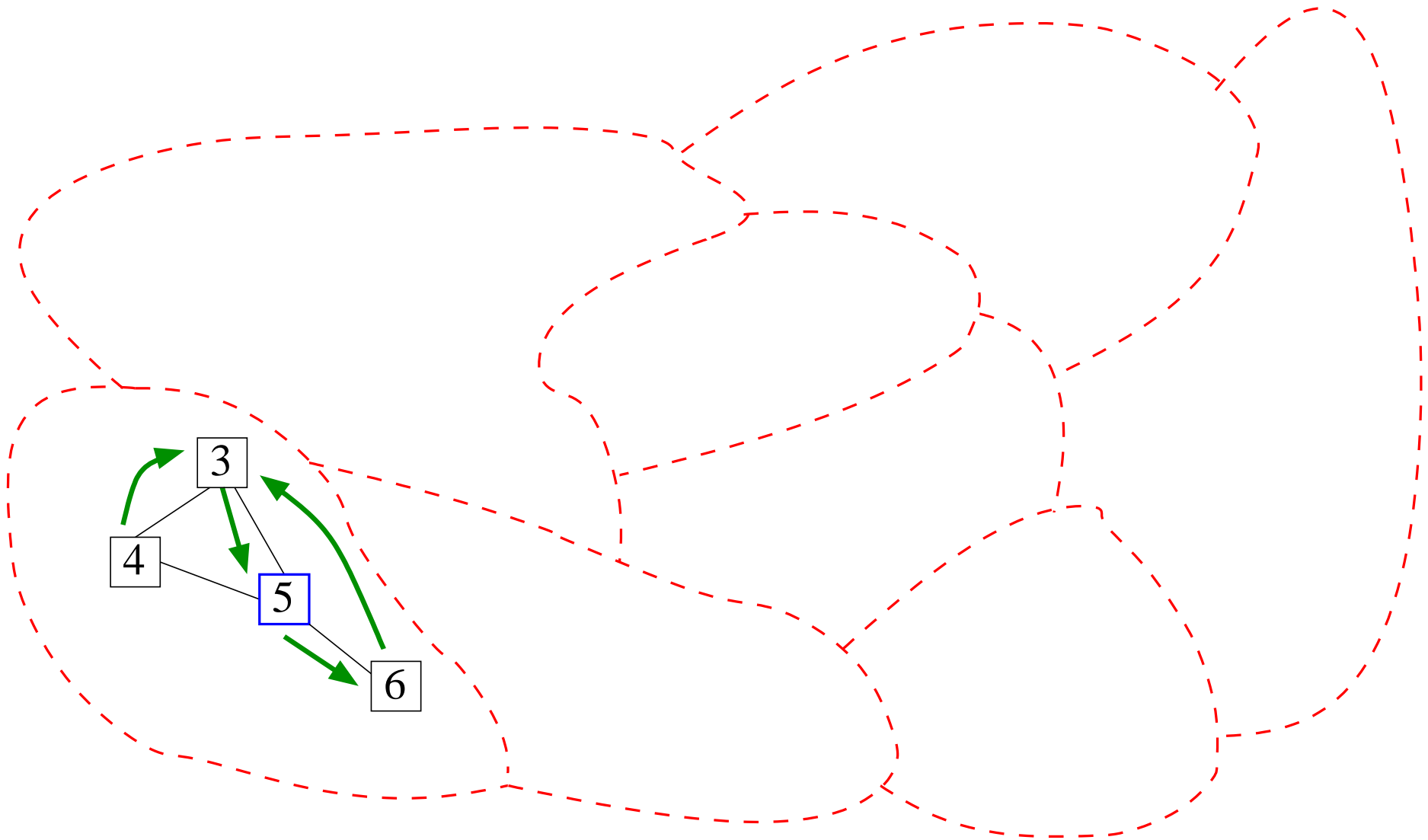


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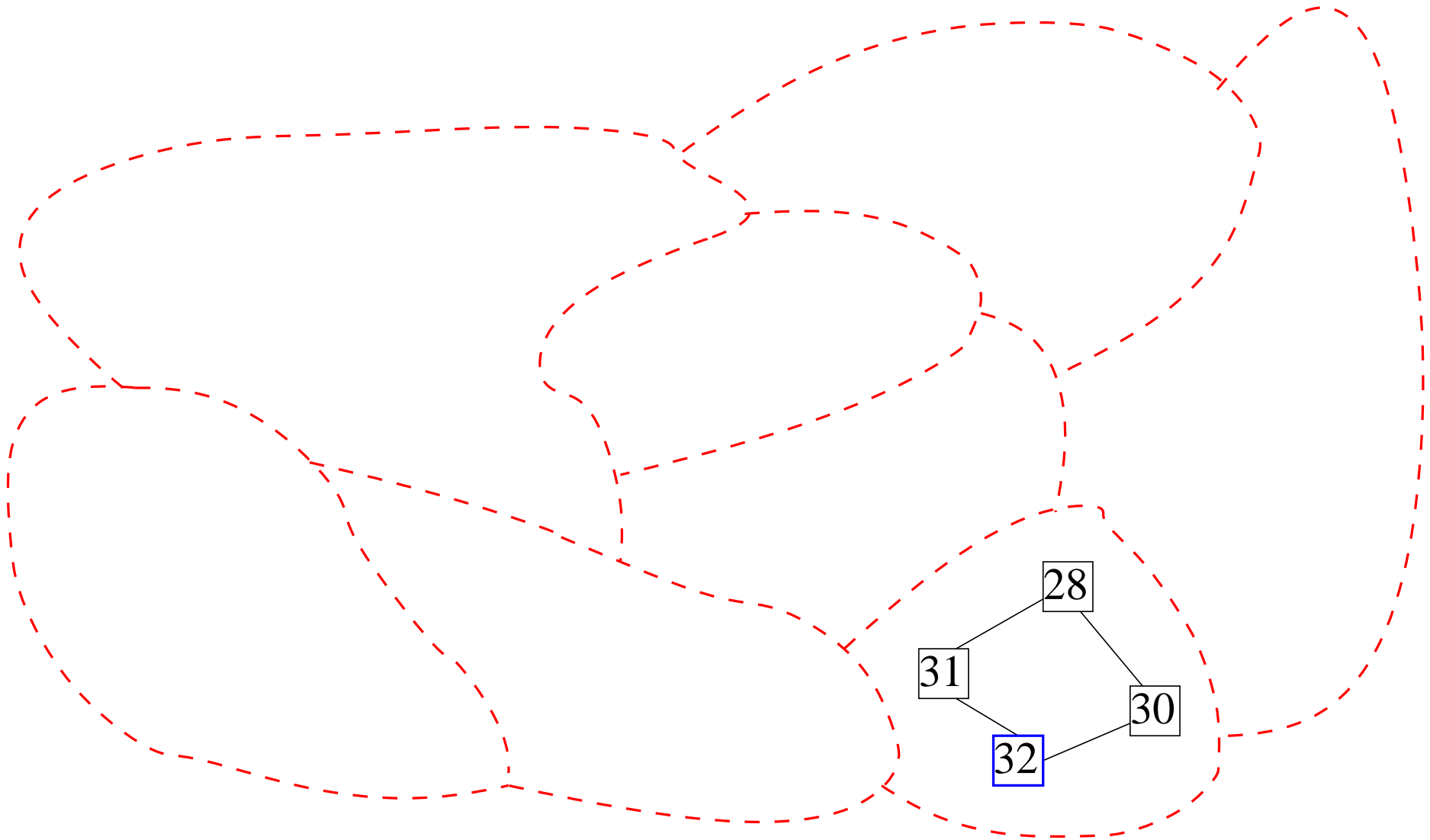


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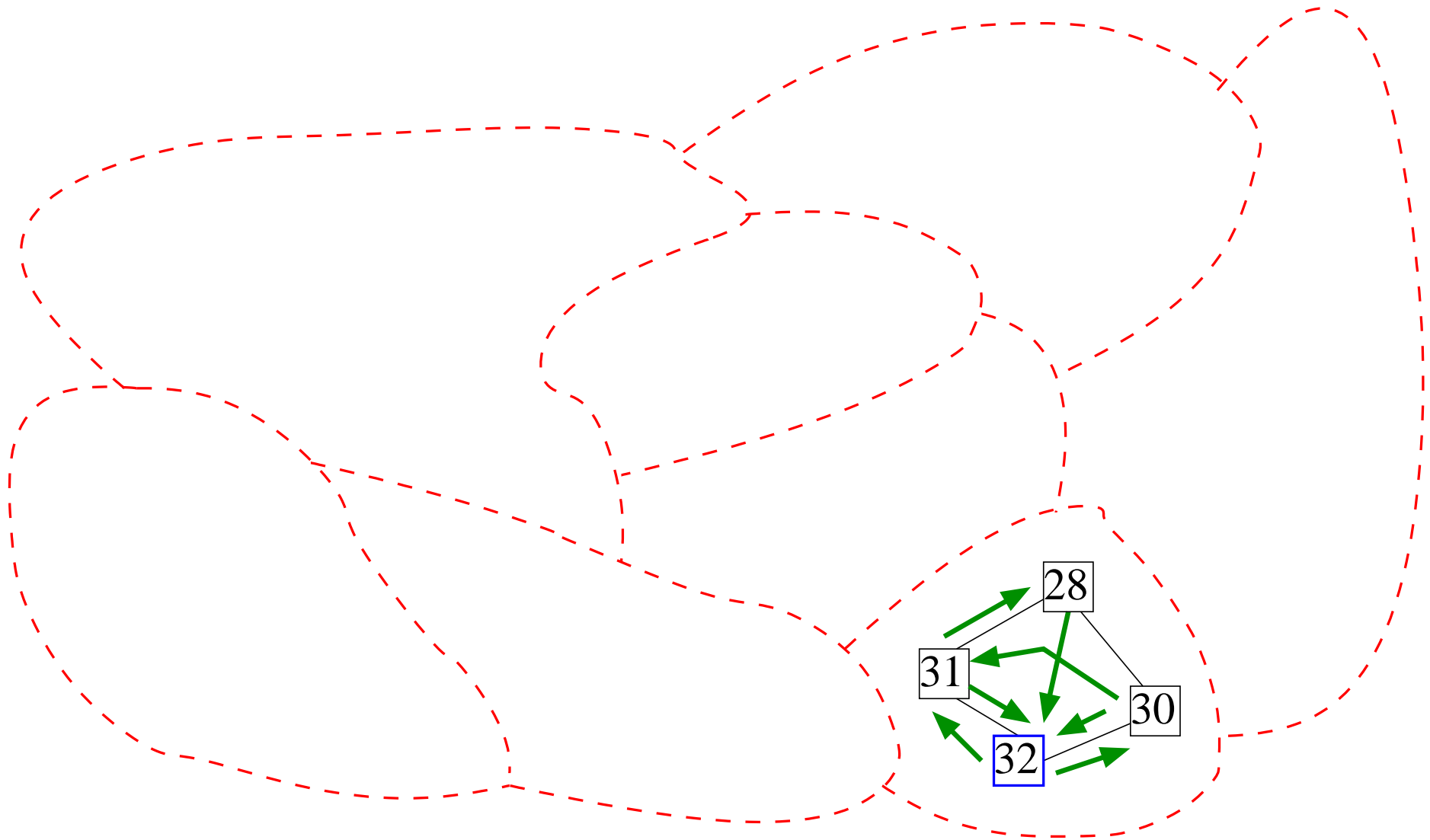


Illustration: Inter-Cluster Grooming

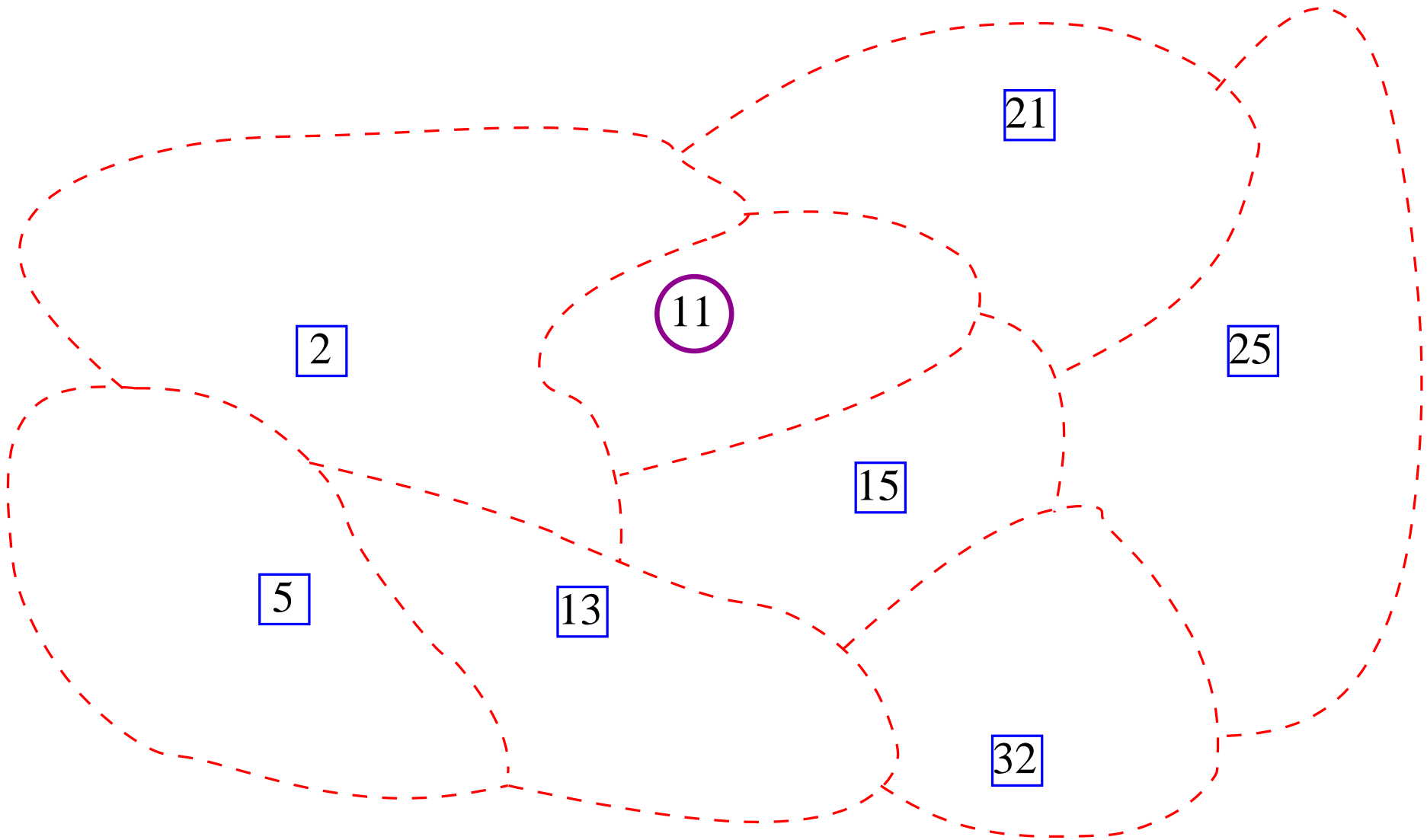
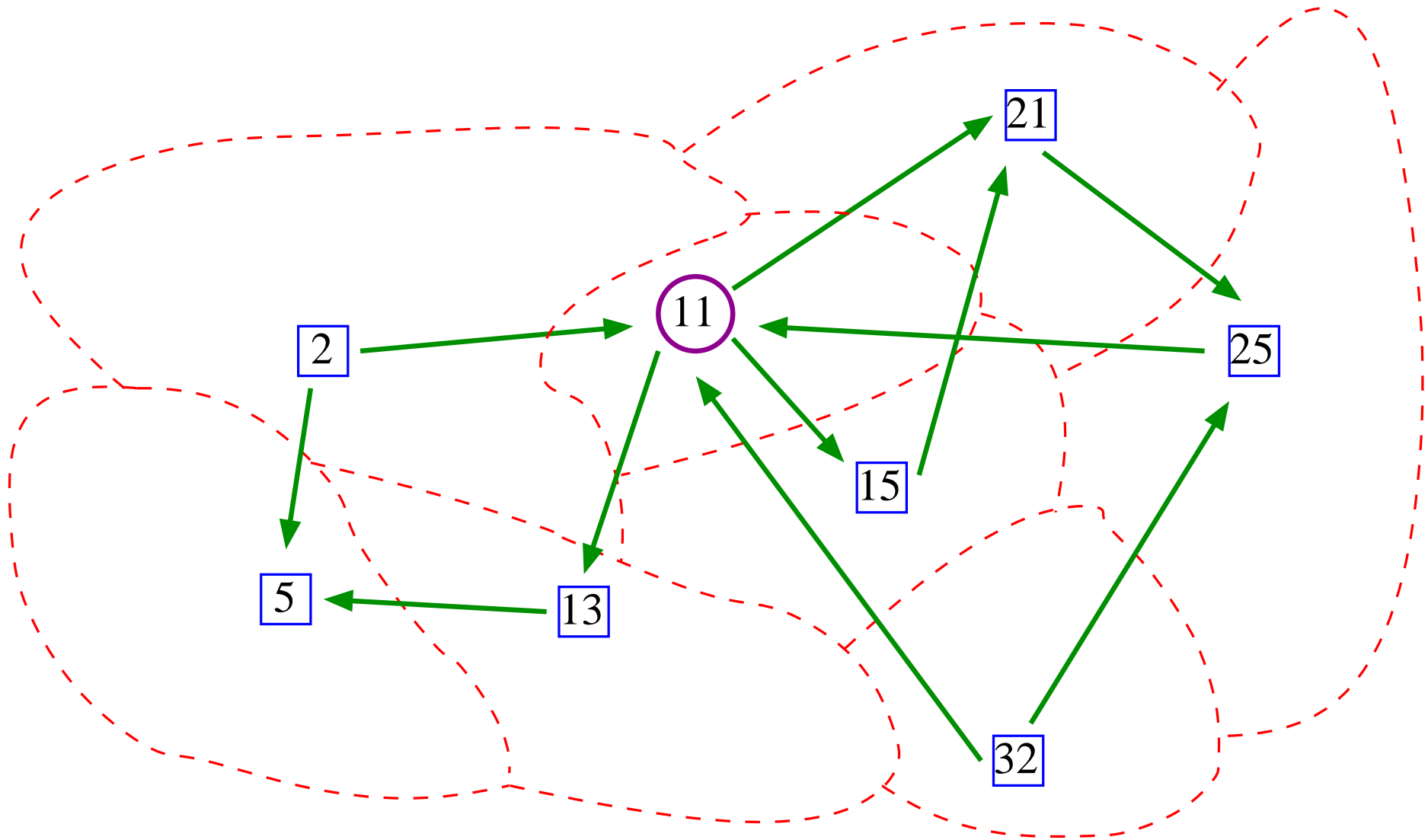


Illustration: Inter-Cluster Grooming



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

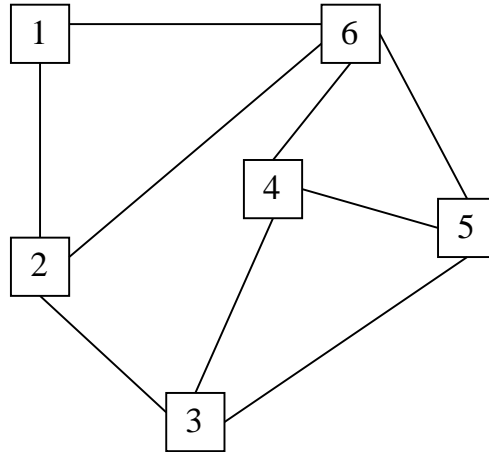
- Widely studied problem in network design and other domains
- Many algorithms exist, but do not address grooming considerations
- *K*-Center problem → good match
 - minimizes max distance from any node to nearest center
 - does not take into account:
 - traffic matrix
 - nodal degrees

Clustering Algorithm for Grooming [CN 2008]

Grooming considerations for clustering:

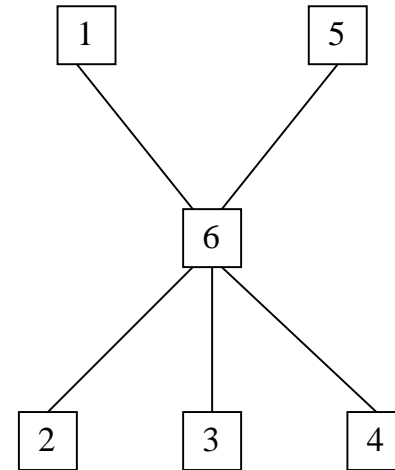
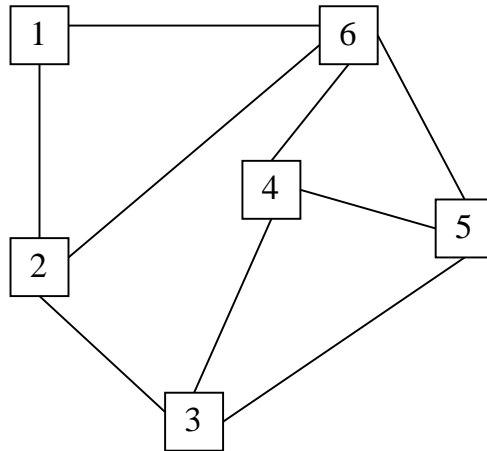
- Effect of number of clusters on hub size and cost objectives
- Composition of each cluster → group nodes with dense traffic
- Effect of cut links connecting to other clusters
- Physical shape of each cluster → avoid linear topology
- Selection of hubs → prefer high degree nodes

The “Virtual” Star Concept



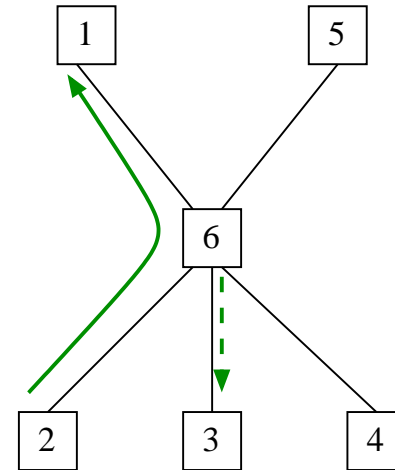
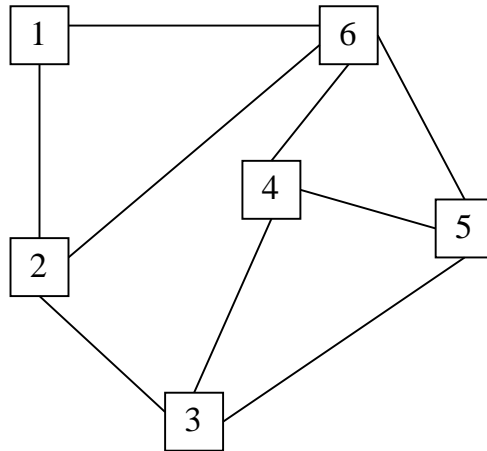
- Any arbitrary topology

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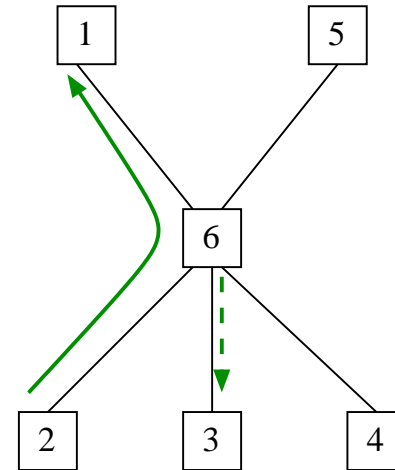
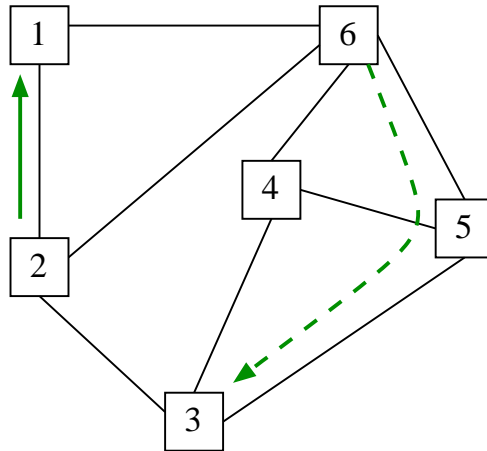
- Any arbitrary topology
- View as star to determine **logical topology / traffic routing**

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

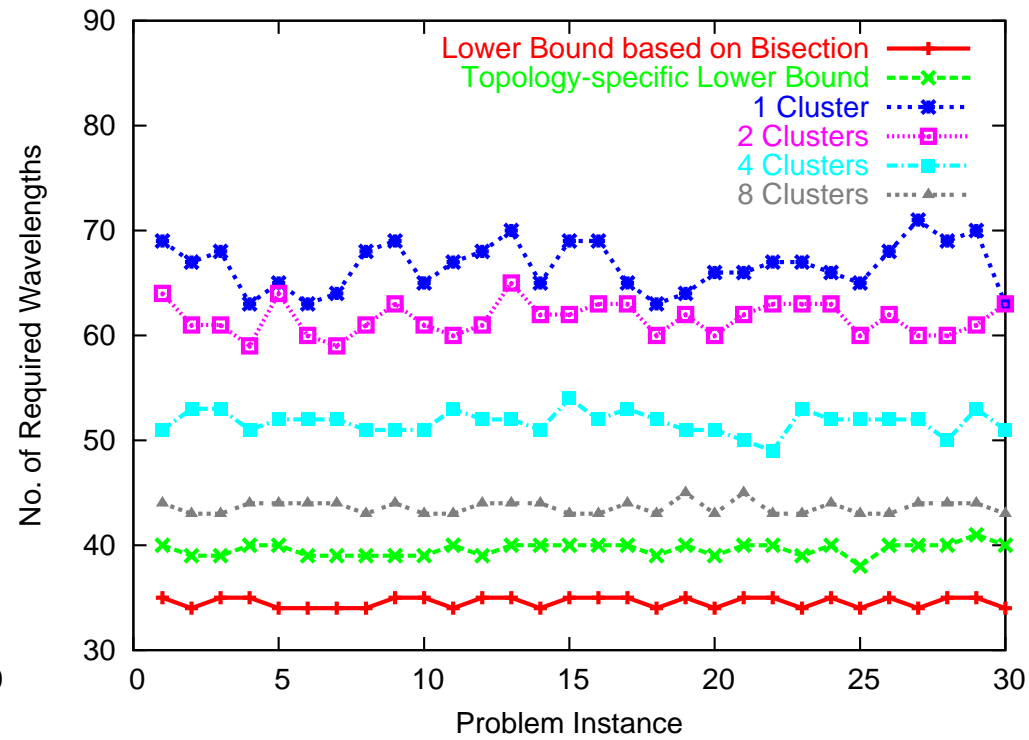
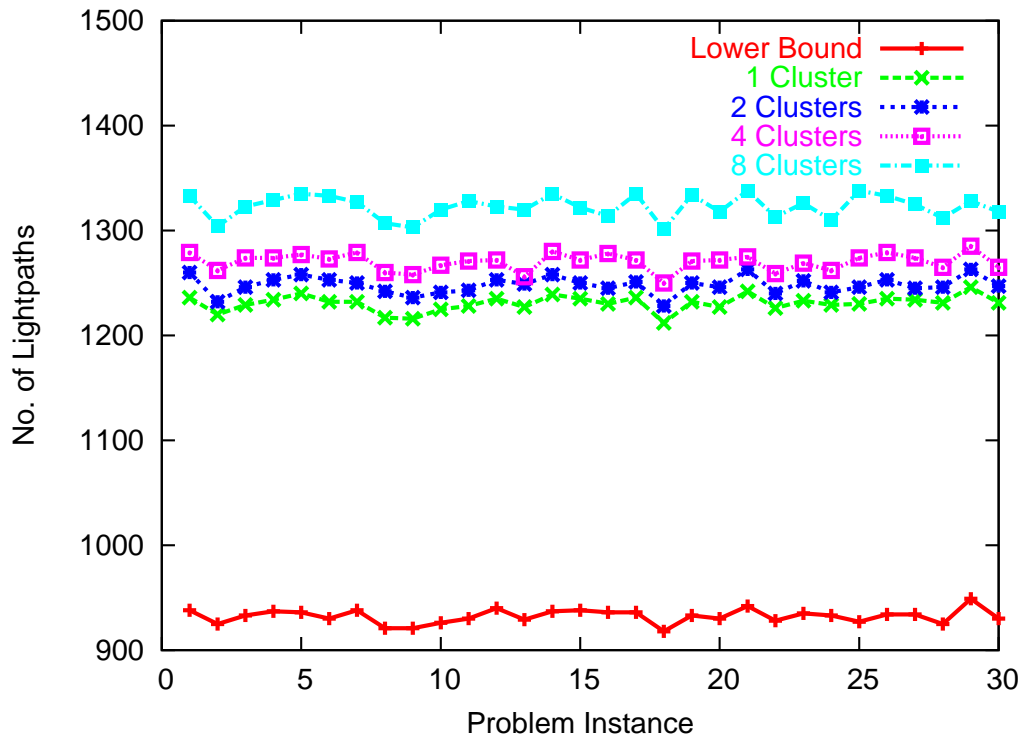
Lower Bounds

- 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 = t/kC
 - used METIS tool to generate good cut
- Bounds **independent** of grooming method

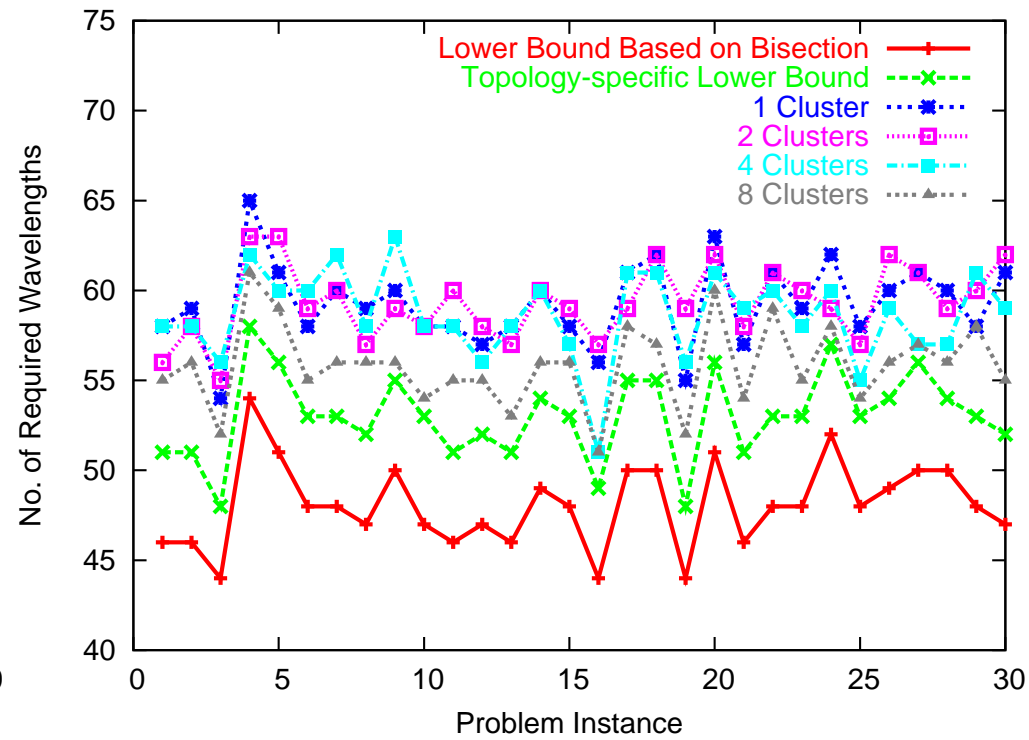
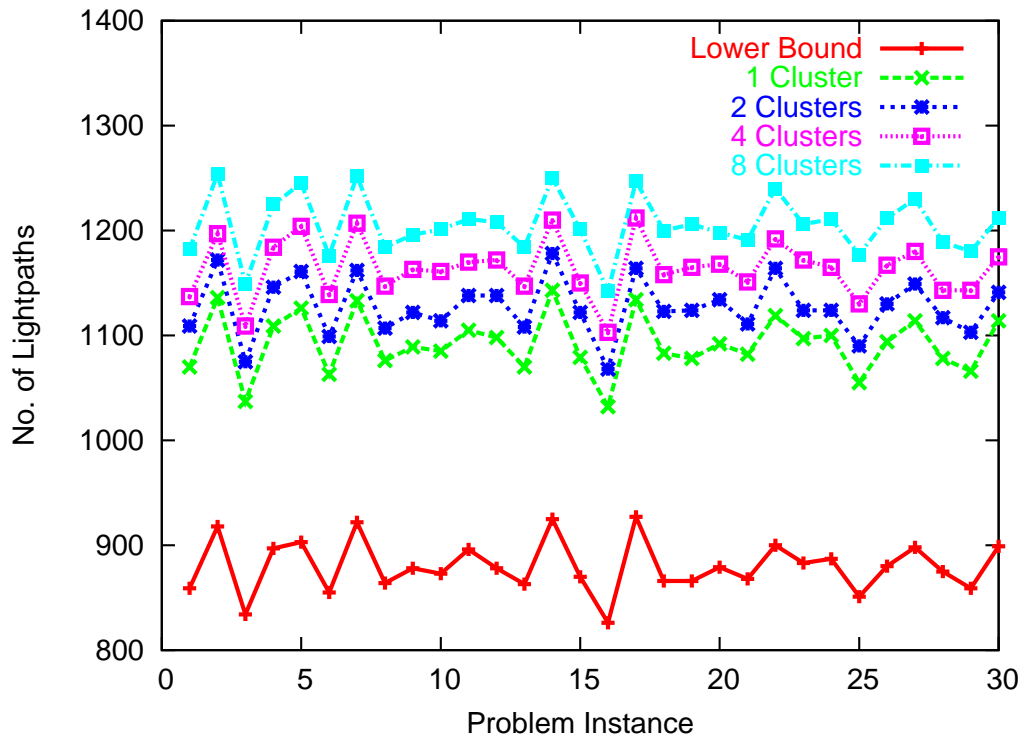
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Results: 32-Node Network, Locality Traffic



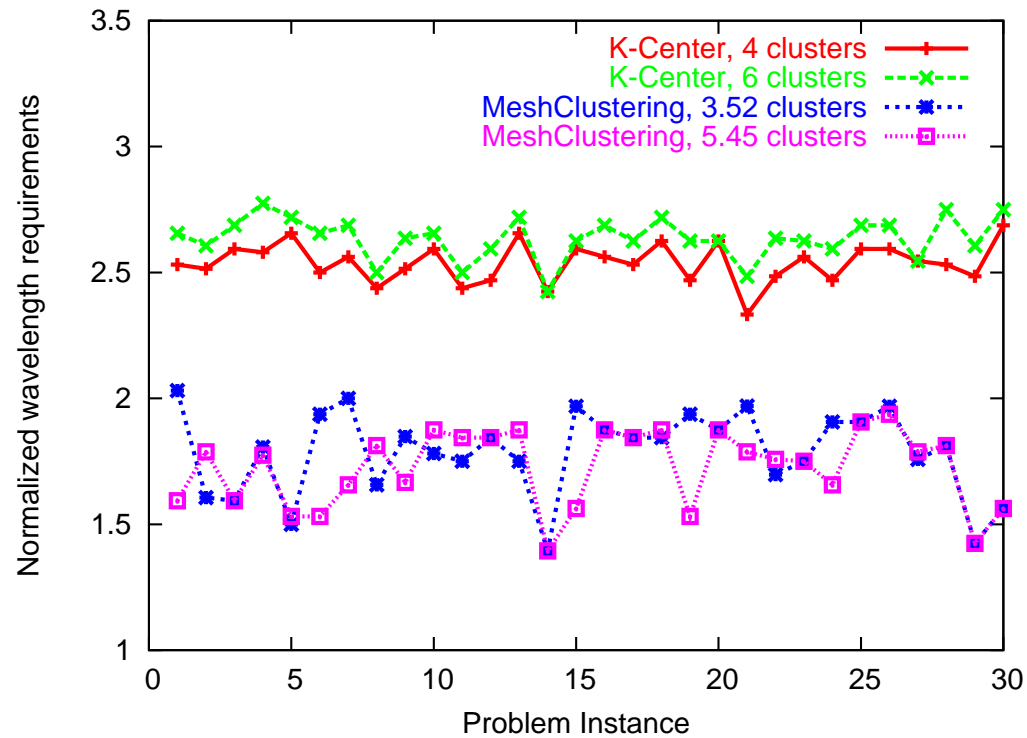
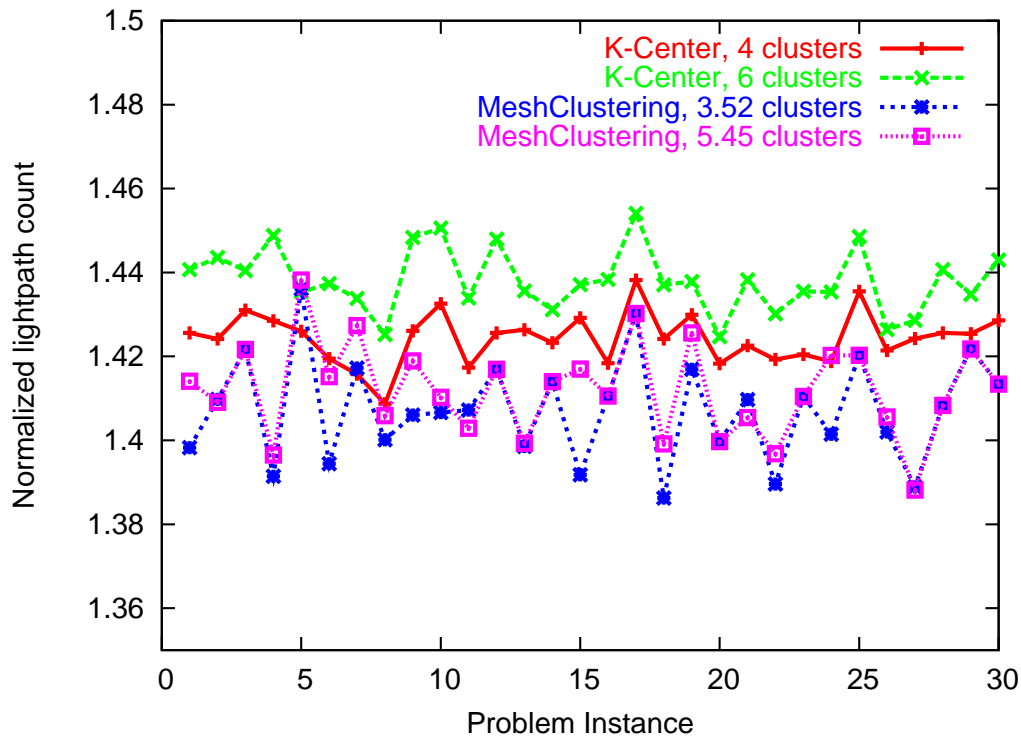
Results: 32-Node Network, Random Traffic



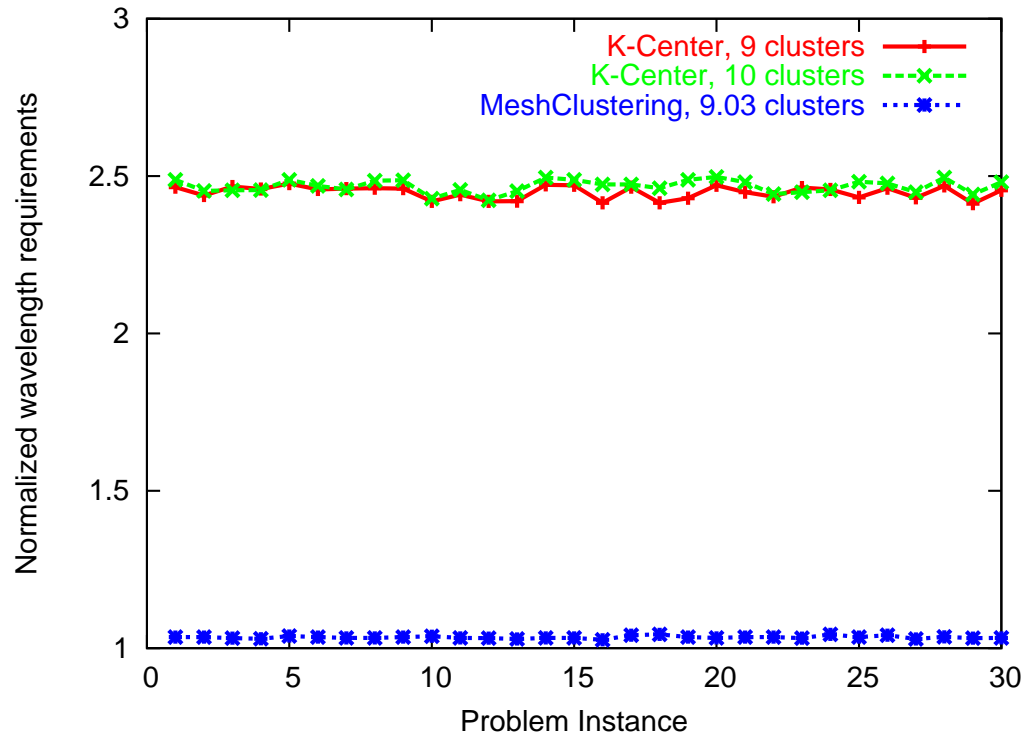
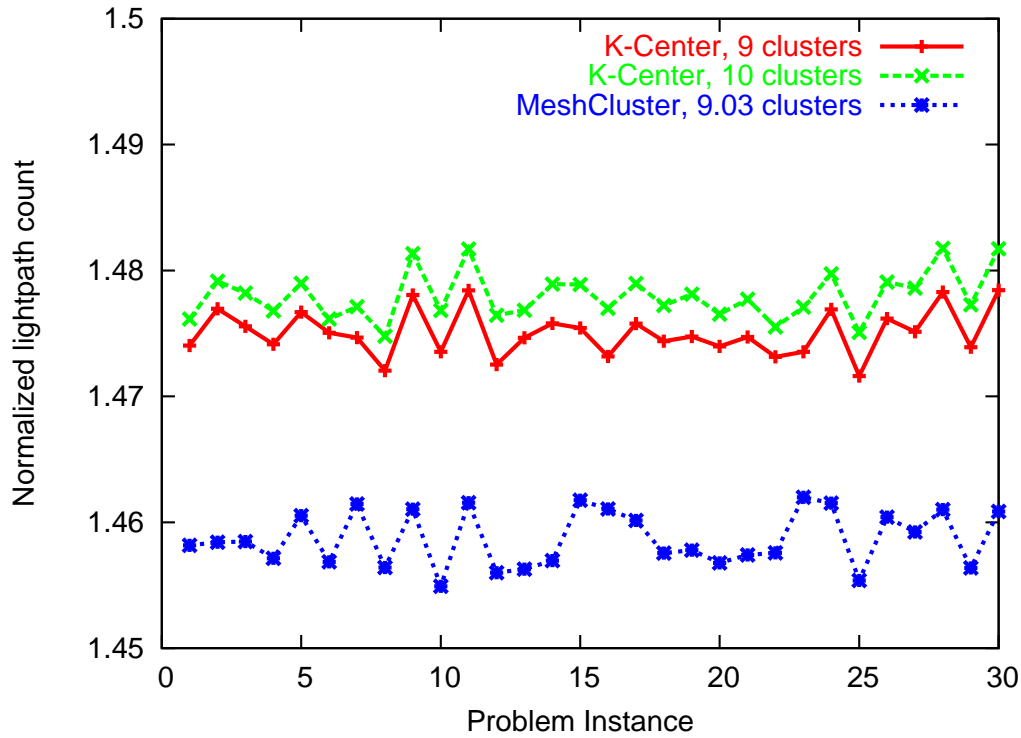
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#Clusters	Avg LP Length	Avg Max Hub Degree	Wavelengths
1	3.17	266	60
2	3.07	228	60
4	2.93	183	59
8	2.84	143	56

Results: 47-Node Network, Locality Traffic



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