Hierarchical Traffic Grooming in WDM Networks

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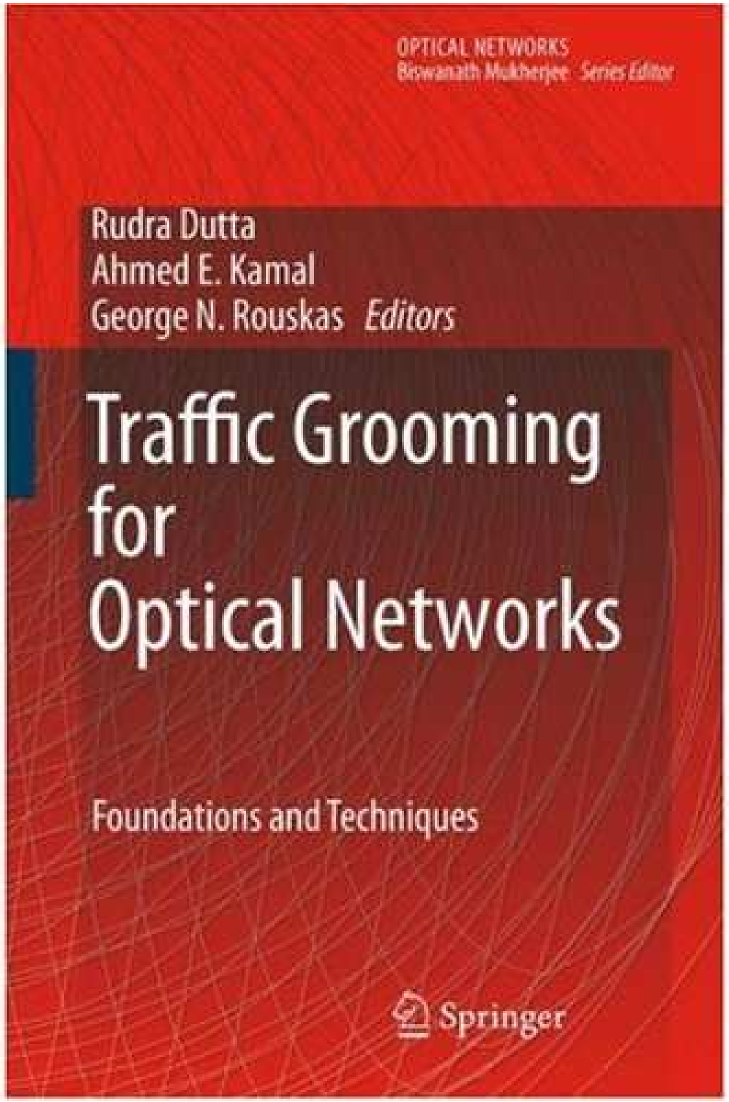
Upcoming Book



Outline

- Motivation and problem defi nition
- Complexity results and implications
- Hierarchical grooming in rings
- Hierarchical grooming for general topology networks
  - clustering and hub selection
  - logical topology design and traffi c routing
  - RWA
- Results and discussion

Optical Networking Trends

- Increasing data rates
  OC-48 (2.5 Gbps) $\longrightarrow$ OC-768 (40 Gbps) and 100 GbE
- Increasing fi ber capacity
  Dense WDM $\longrightarrow$ 100s of λs per fi ber
- Improving fi ber technology
  Optical signals may travel longer without regeneration (OEO)
- Improving OXC technology
  Higher port counts, faster confi guration 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?

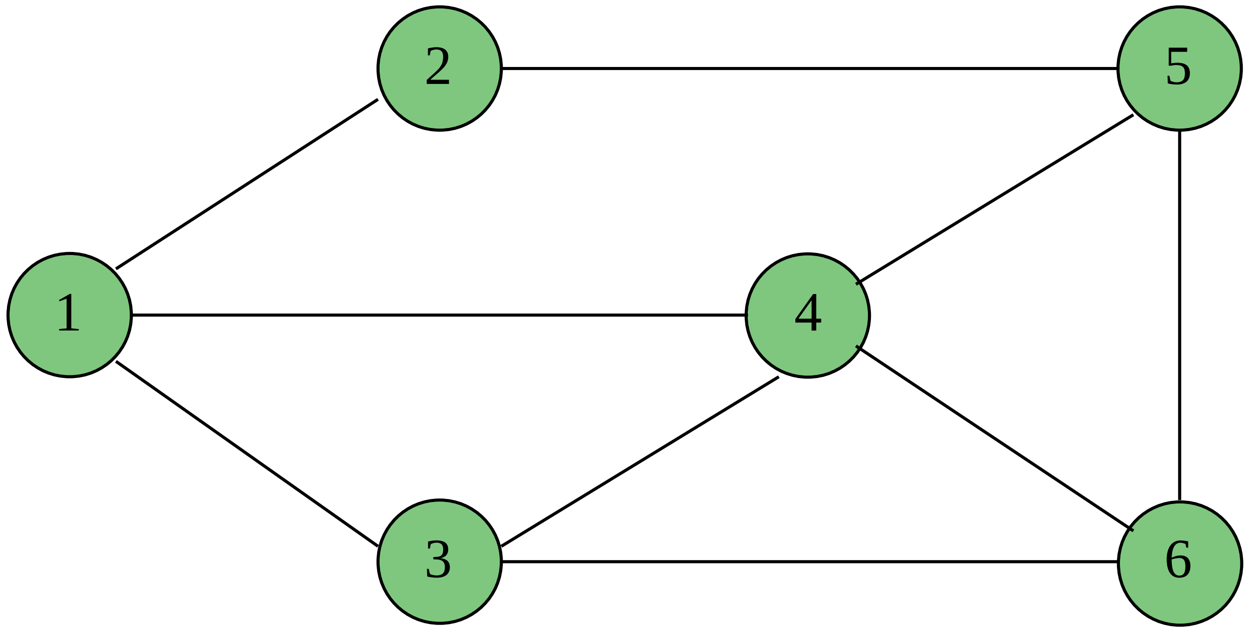
  Efficiently set up lightpaths and groom (i.e., pack/unpack, switch, route, etc.) low-speed traffic onto high capacity wavelengths so as to minimize network resources

- Requires MUX/DEMUX and ADM/OADM devices
- But: involves much more than simple multiplexing techniques

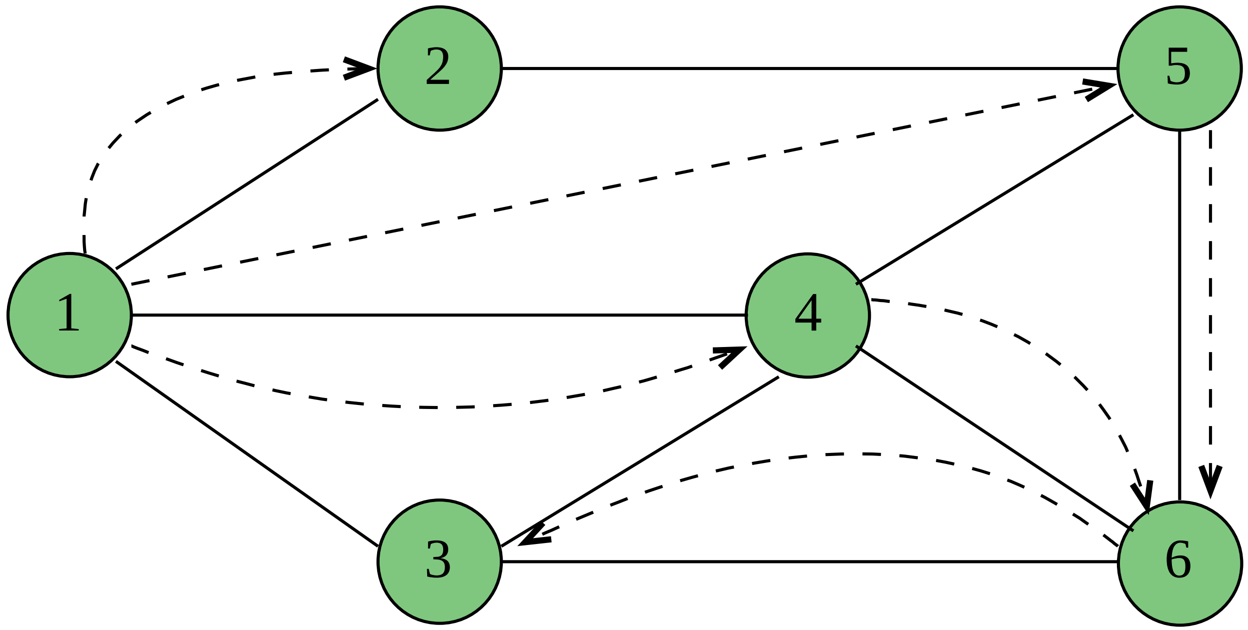
Traffic Grooming as Optimization Problem

- Inputs to the problem:
  - physical network topology (fi ber layout)
  - traffi c matrix $T = [t_{sd}] \longrightarrow$ int multiples of unit rate (e.g., OC-3)
- Output:
  - logical topology
  - lightpath routing and wavelength assignment (RWA)
  - traffi c grooming on lightpaths
- Objectives:
  - minimize total # of OEO ports in the network ($\longleftrightarrow$ # of lightpaths)
  - limit the number of required wavelengths

Traffic Grooming Subproblems

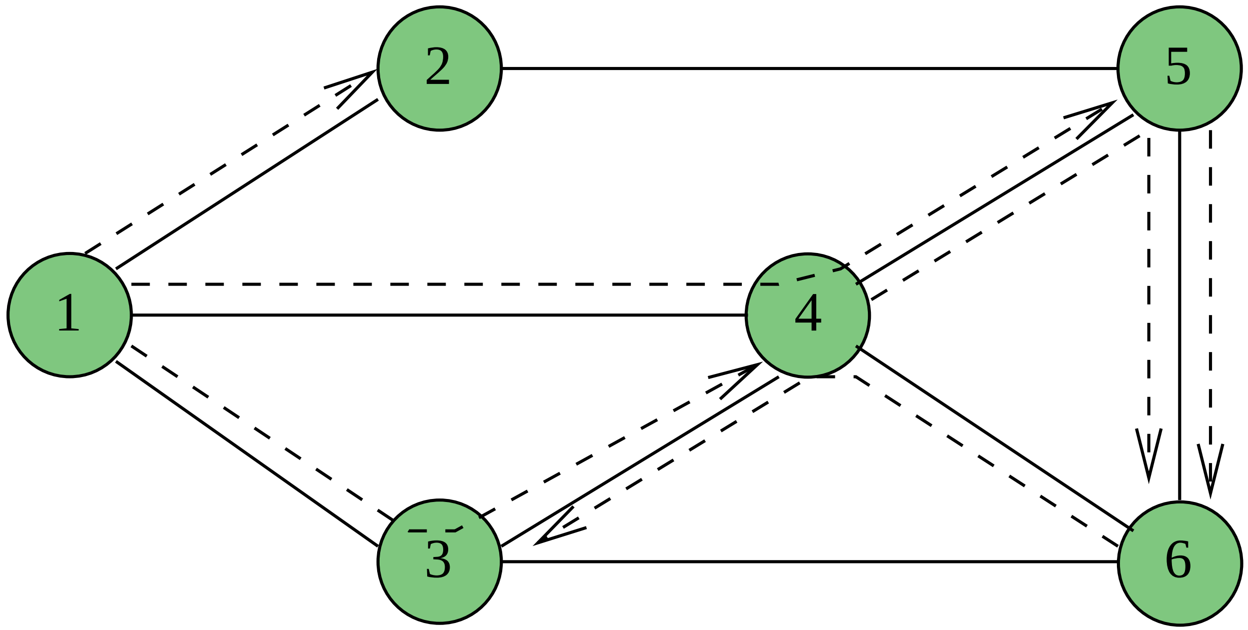


Traffic Grooming Subproblems



- Logical topology design ⟶ determine the lightpaths to be established

Traffic Grooming Subproblems



- Logical topology design $\longrightarrow$ determine the lightpaths to be established
- Lightpath routing $\longrightarrow$ route the lightpaths over the physical topology

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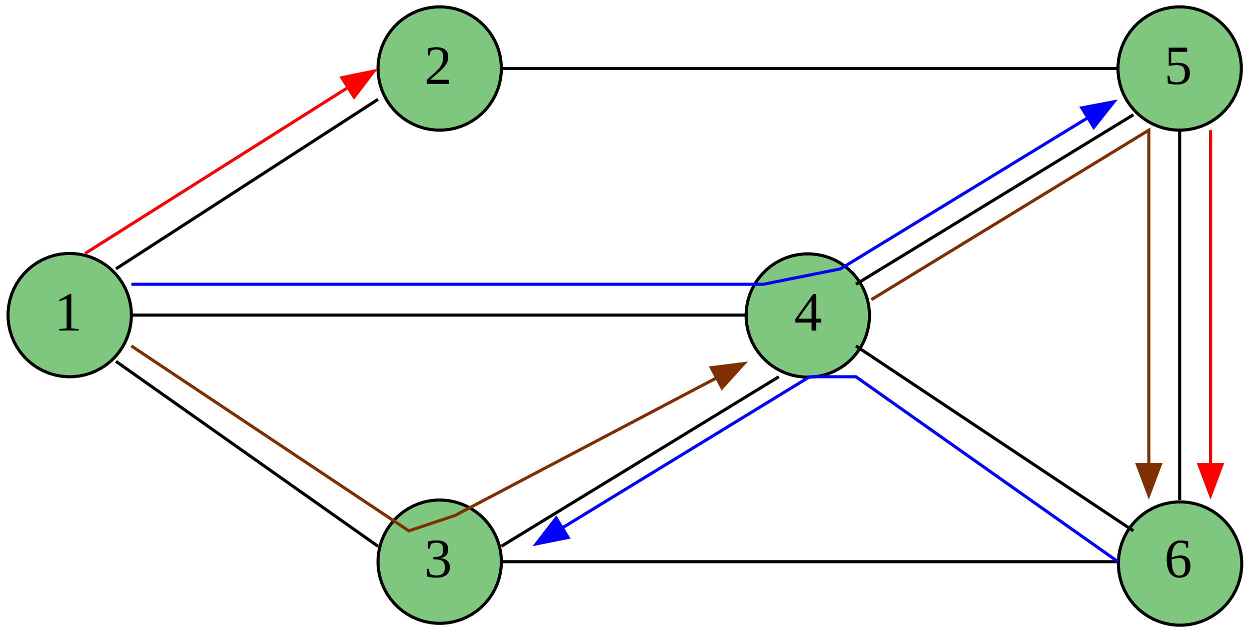

- Logical topology design → determine the lightpaths to be established
- Lightpath routing → route the lightpaths over the physical topology
- Wavelength assignment → assign wavelengths to lightpaths w/o clash

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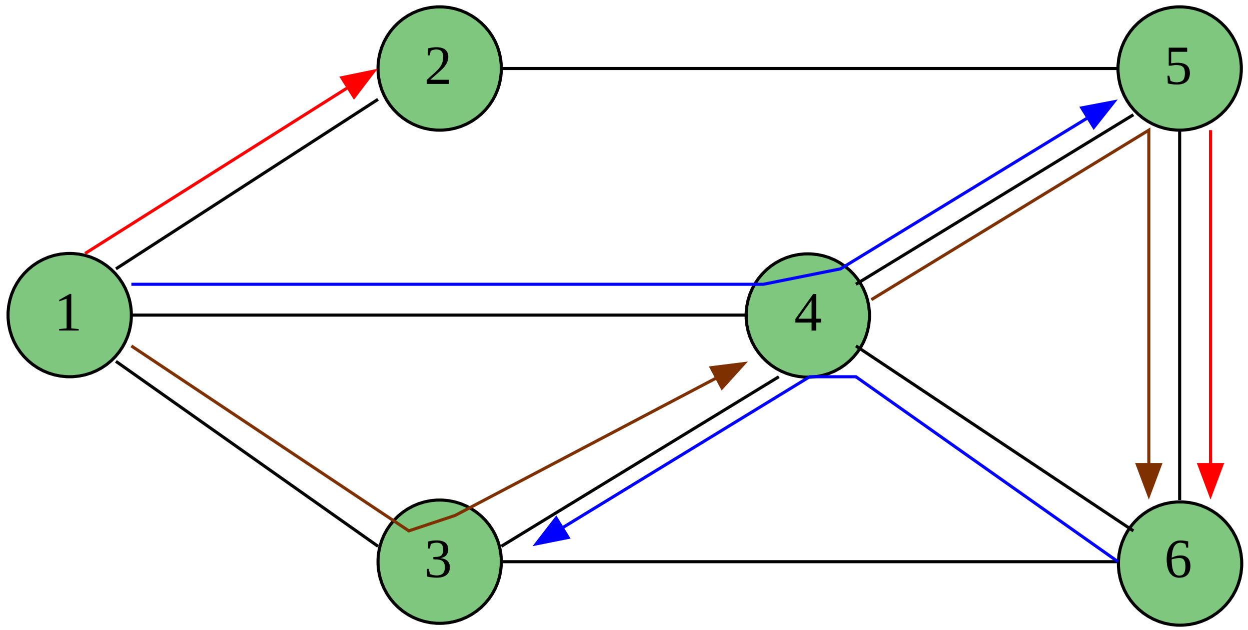

- Logical topology design $\longrightarrow$ determine the lightpaths to be established
- Lightpath routing $\longrightarrow$ route the lightpaths over the physical topology
- Wavelength assignment $\longrightarrow$ assign wavelengths to lightpaths w/o clash
- Traffi c grooming$\longrightarrow$ route traffi c on virtual topology

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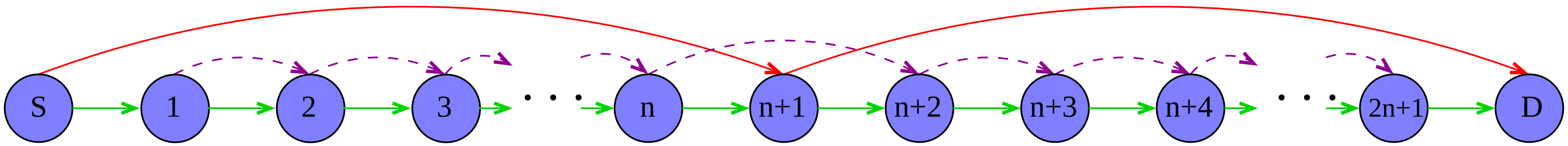
Problem Complexity

- Optimization problem:
  - can be formulated as integer linear problem (ILP)
  - is NP-hard in general $\longrightarrow$ 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]



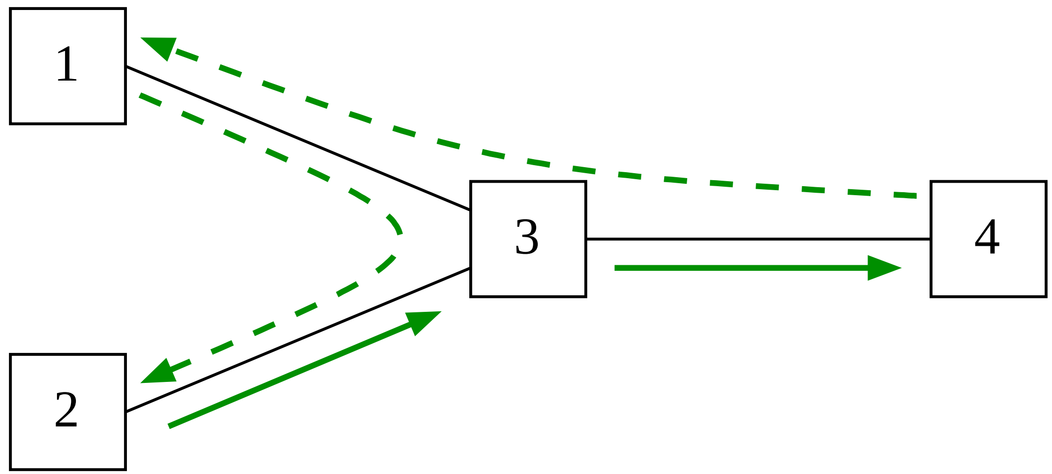
- Problem instance:
  - unidirectional linear (path) network
  - logical topology and RWA is given
  - traffi c either bifurcated or not bifurcated
- Objective: fi nd a grooming of traffi c onto the lightpaths
- Result: problem is NP-complete $\longrightarrow$ reduction from *Subset Sums*

Implications

The problem is not simplifi ed by assuming

- fi xed 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 $\longrightarrow$ 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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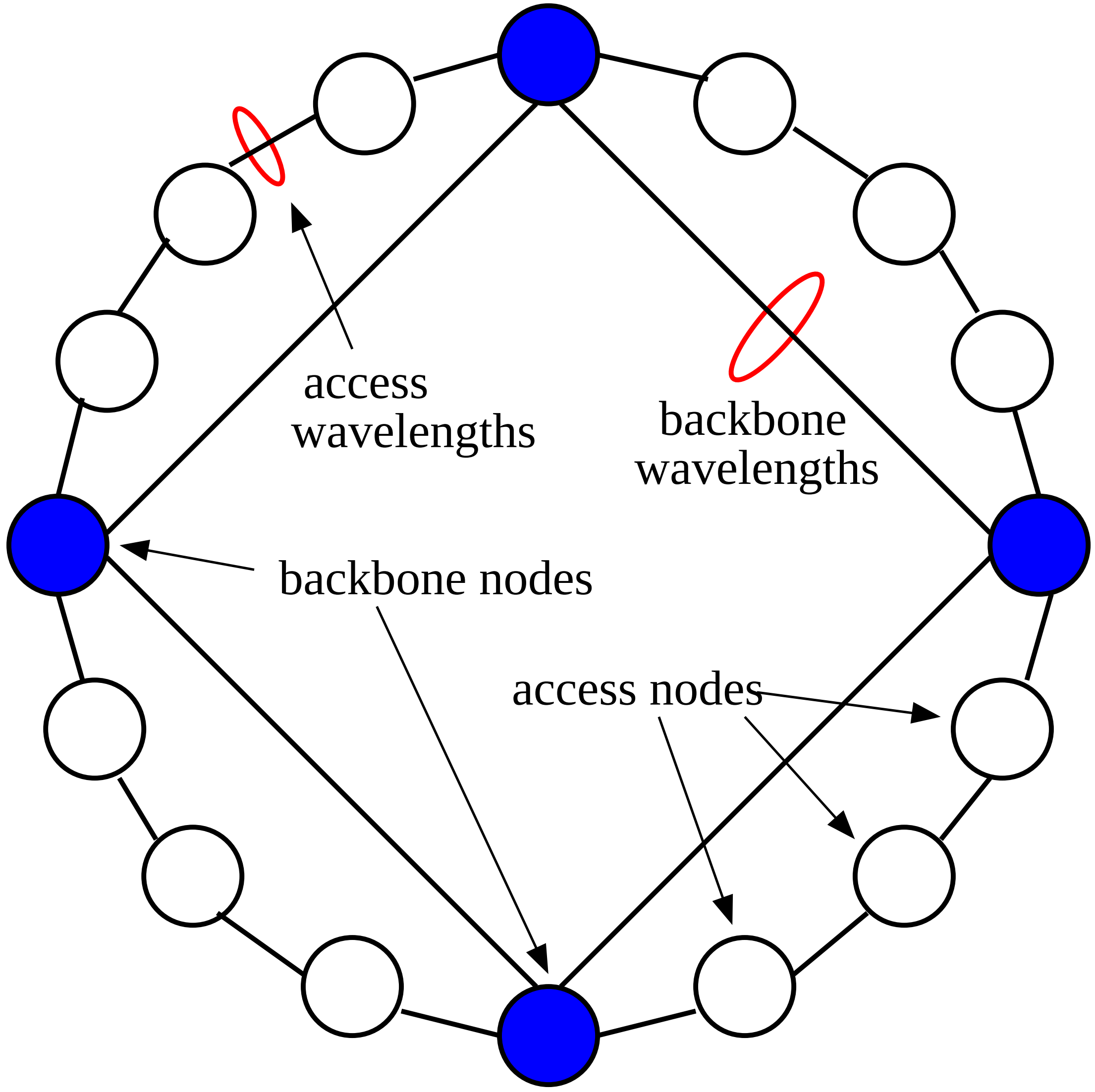
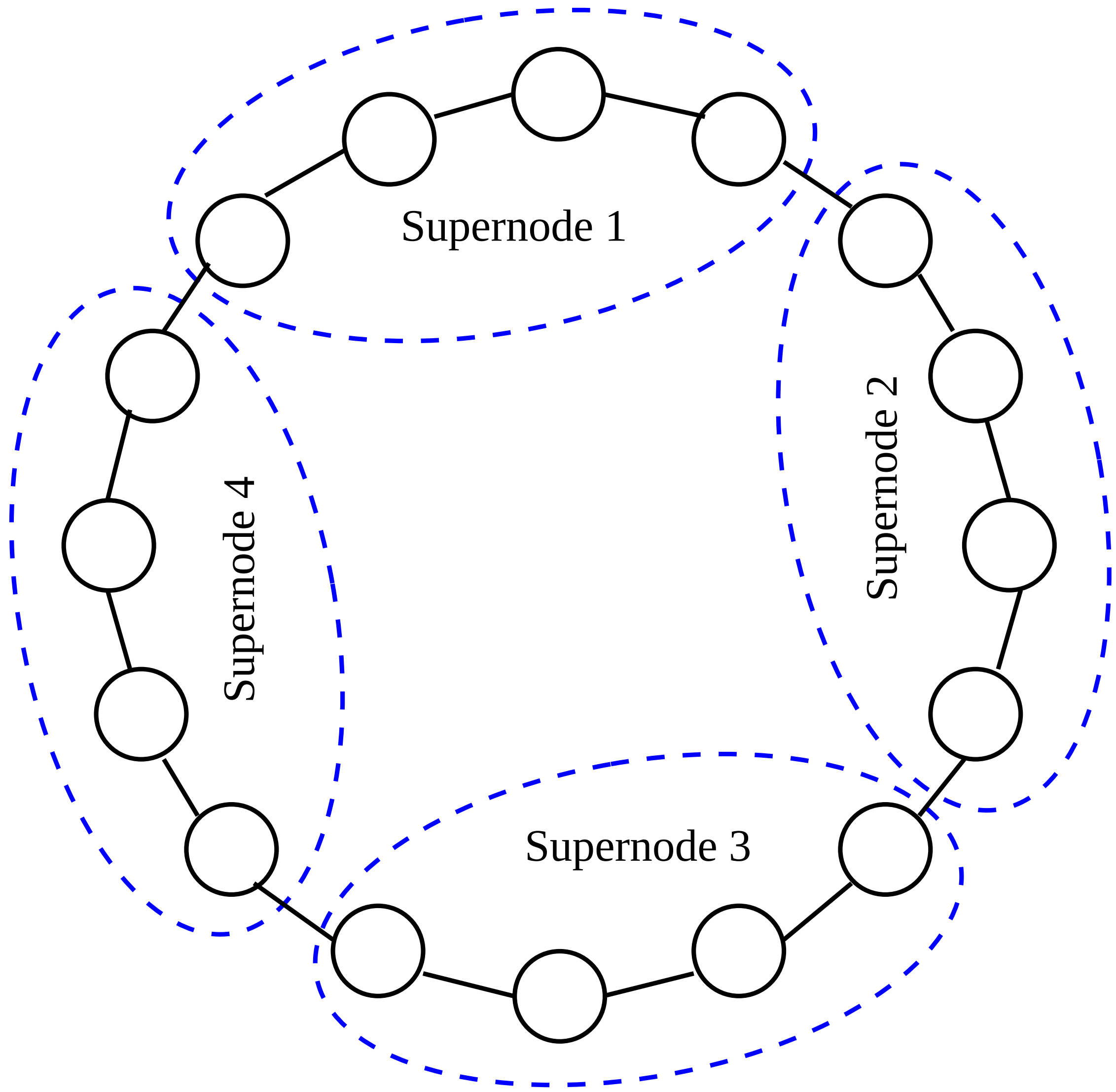
Hierarchical Grooming in Rings

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

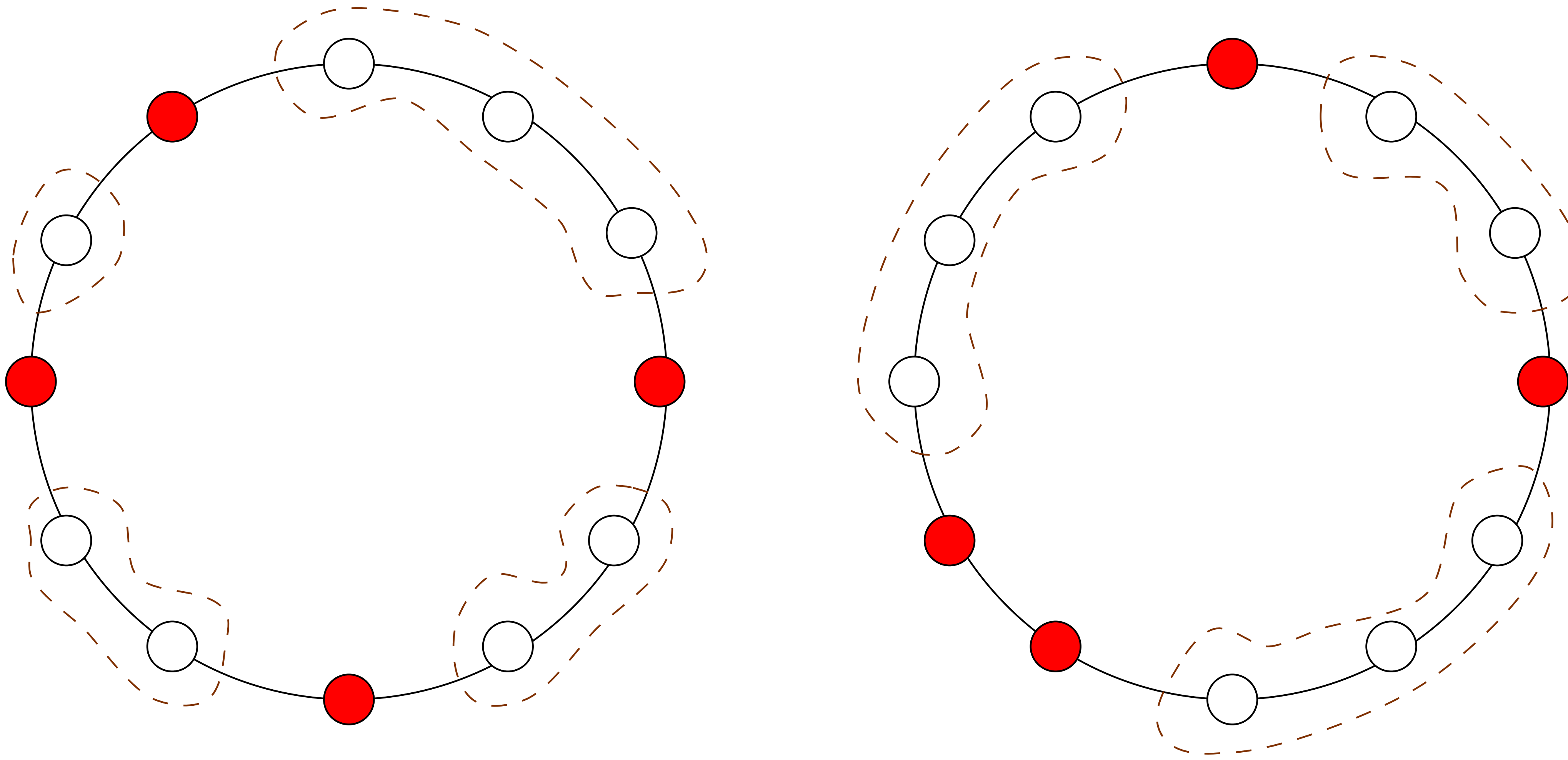
Ring Embeddings



Super-Node Archtecture



Generalized Hub Archtecture



(a)

(b)

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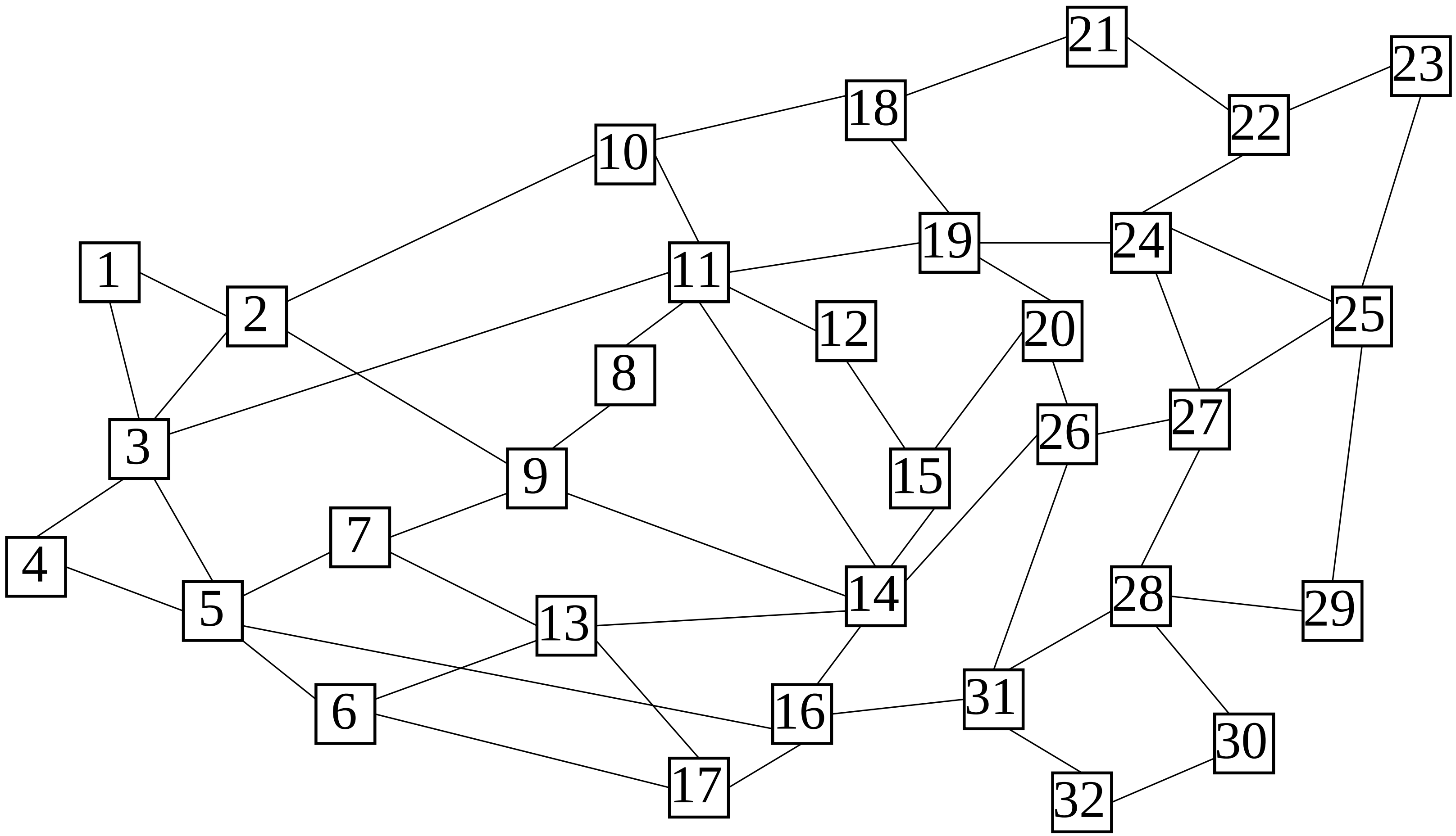
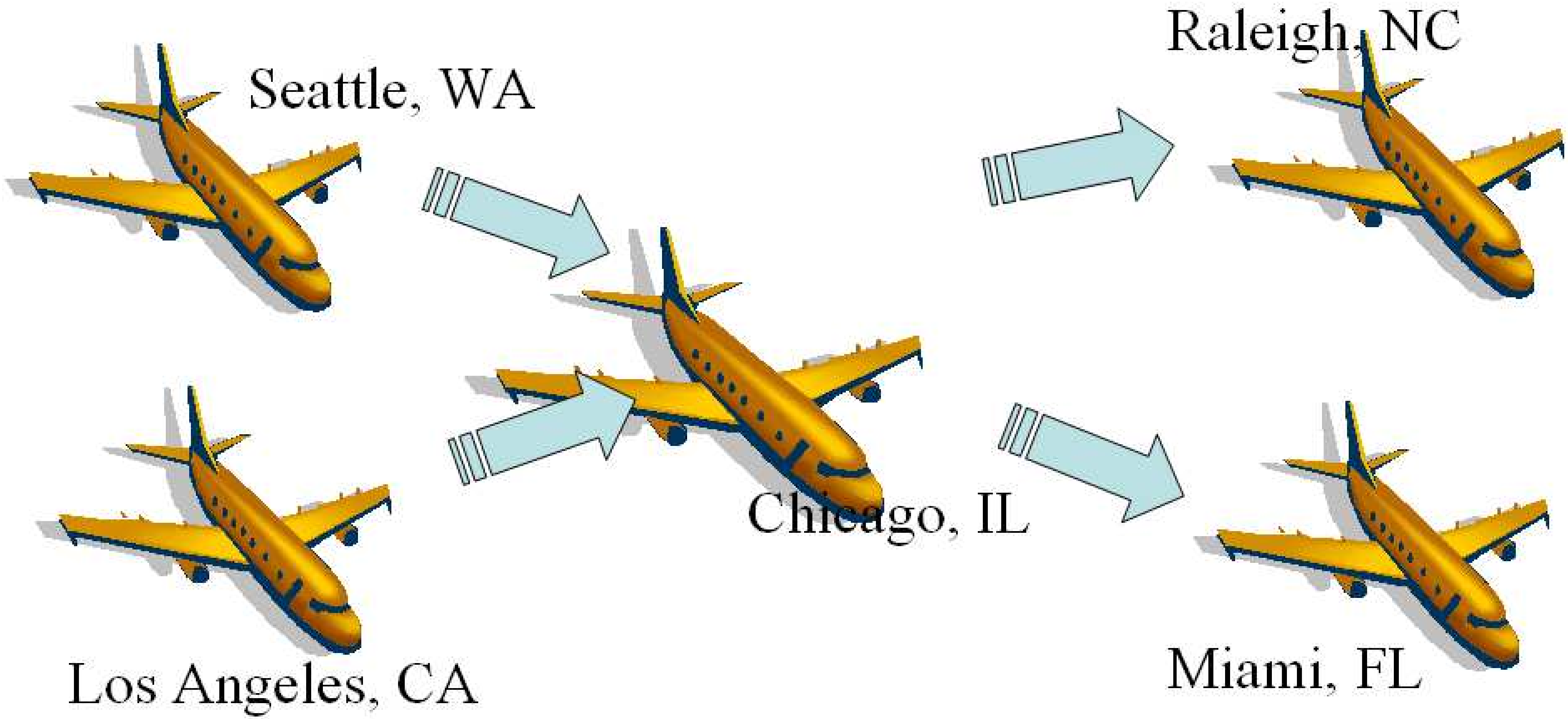
Grooming in General Topology Networks



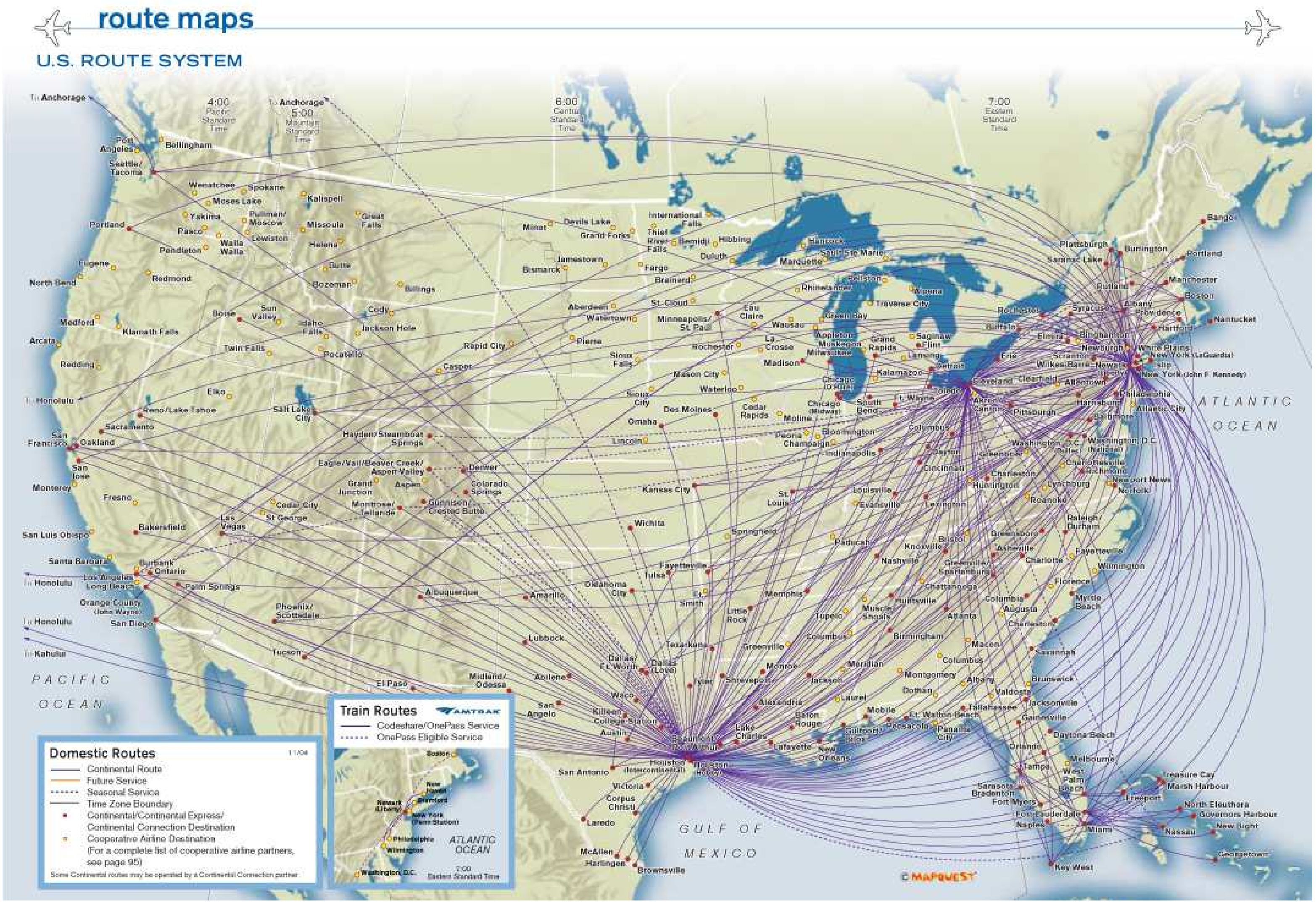
Approaches

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



Airline Traffic Analogy (2)



Hierarchical Grooming Phases [ToN 2008]

1. Clustering and hub selection
2. Logical topology design and traffi c 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

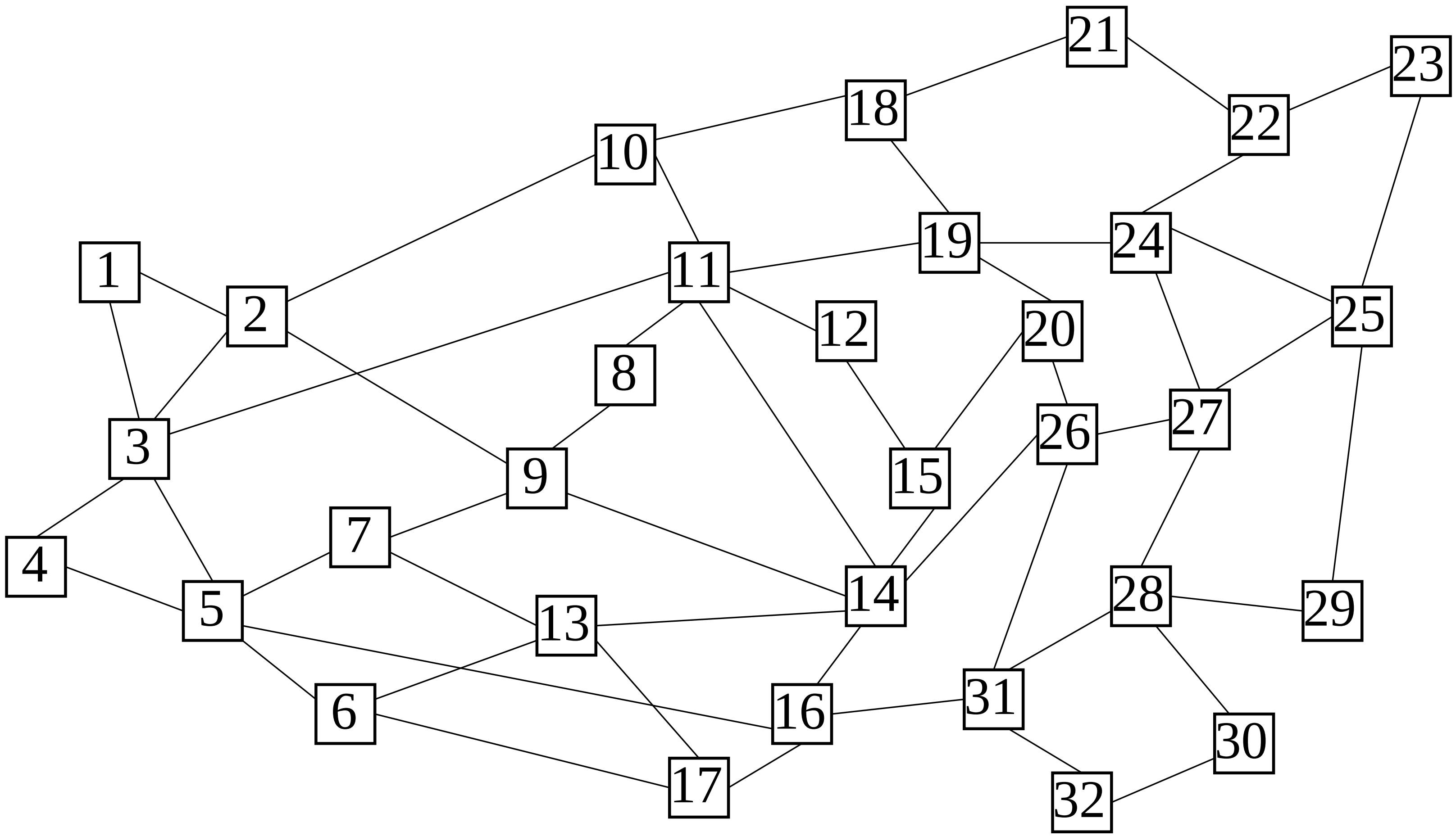


Illustration: Clustering

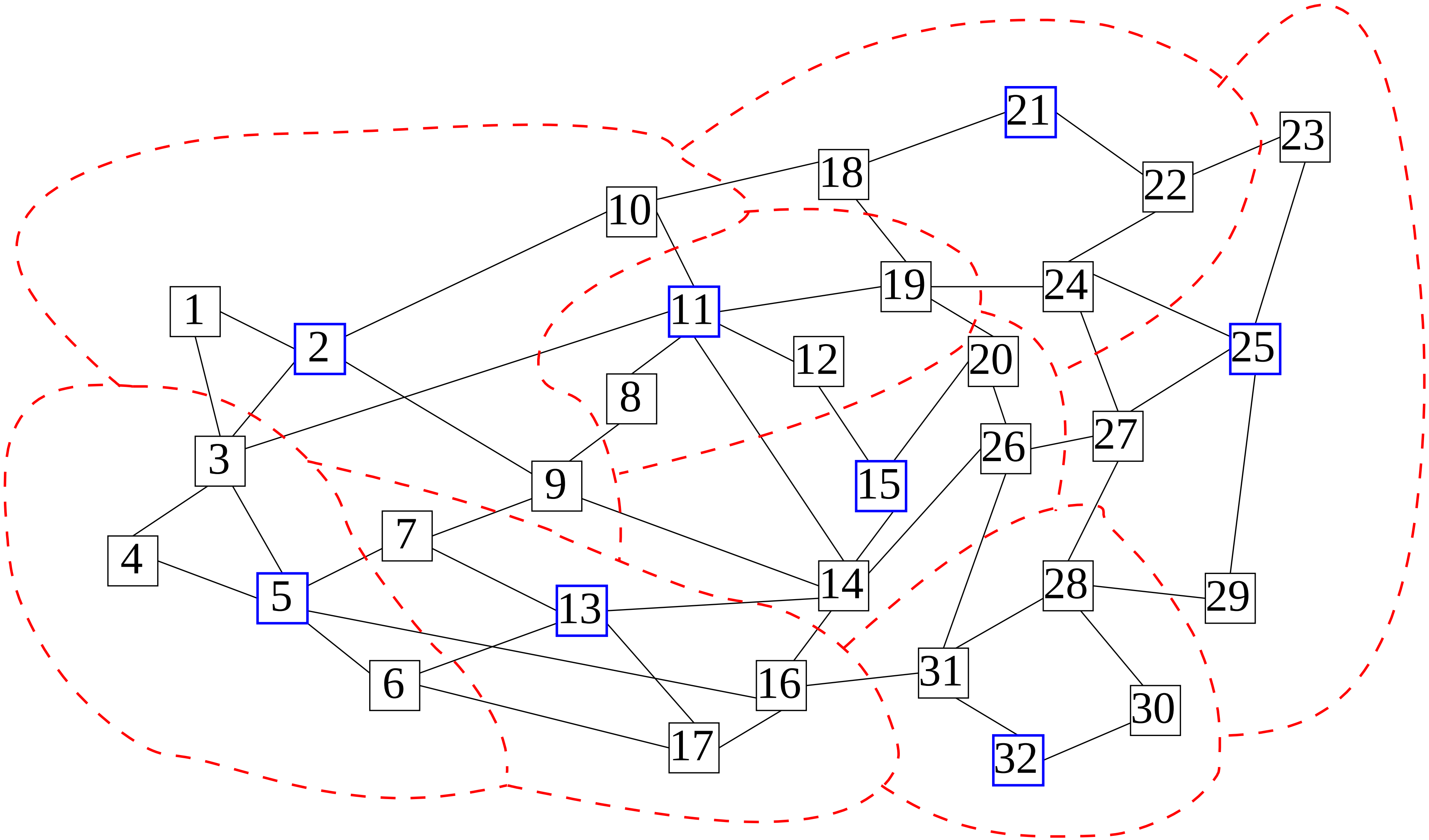
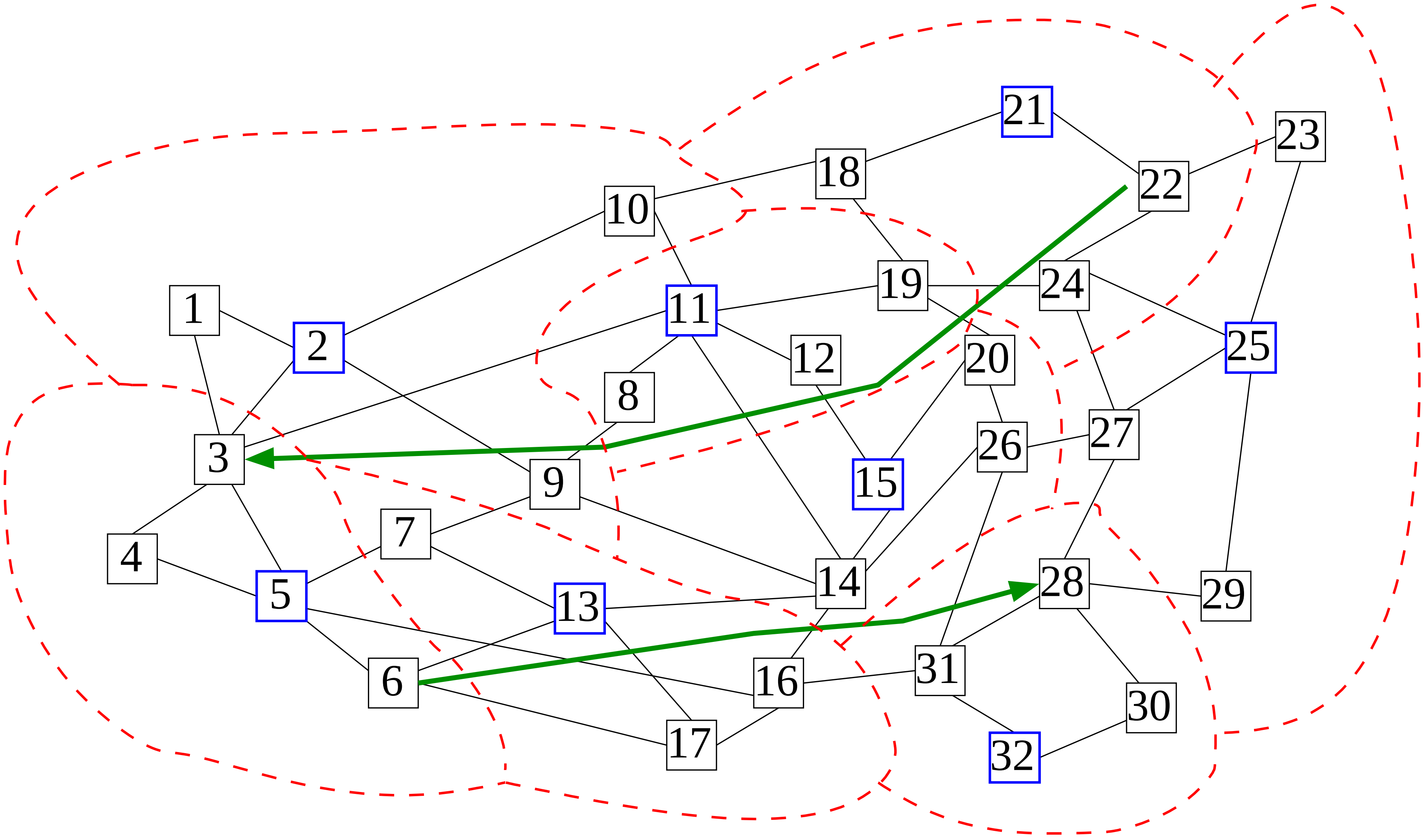


Illustration: Reduction



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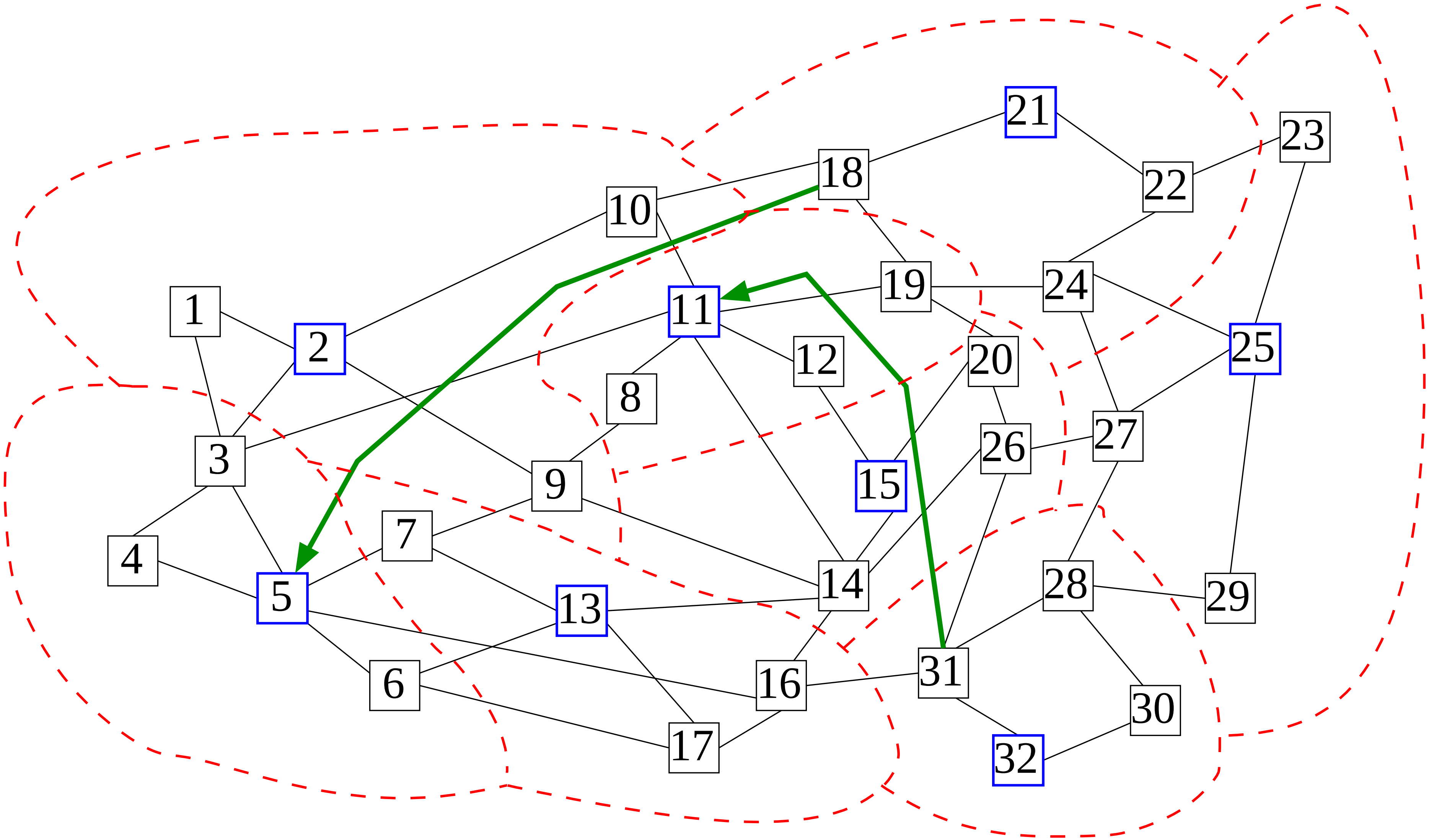
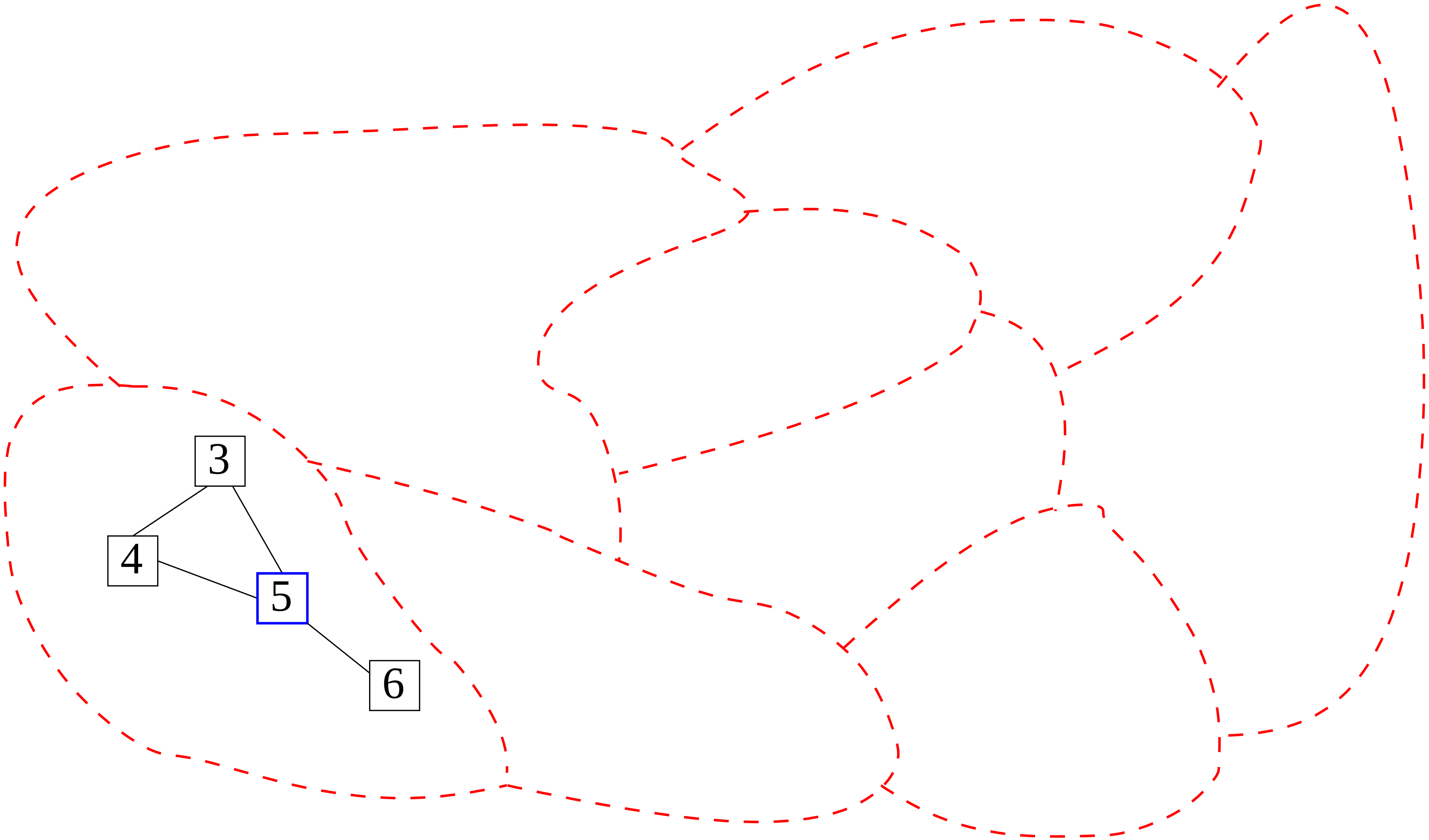


Illustration: Intra-Cluster Grooming



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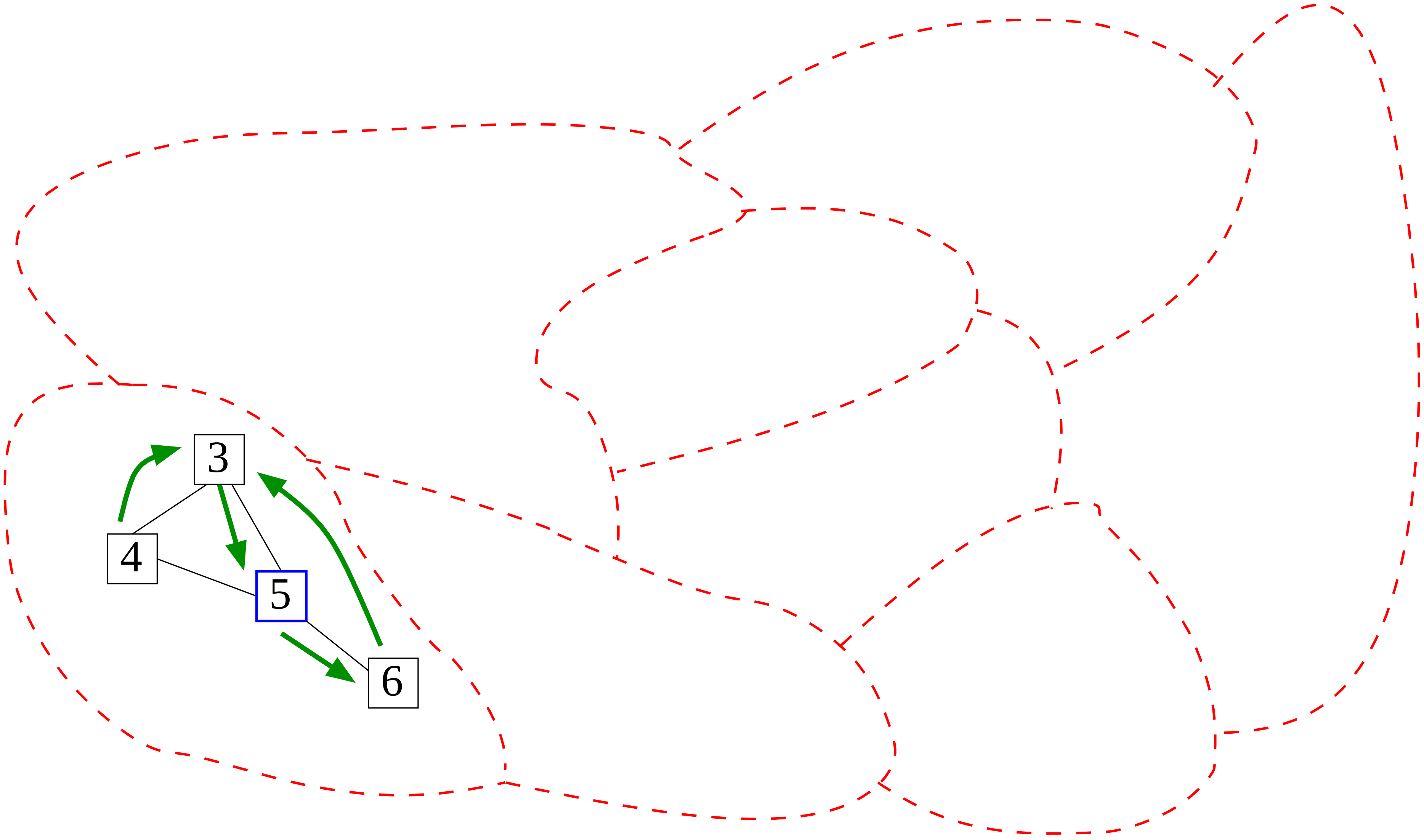

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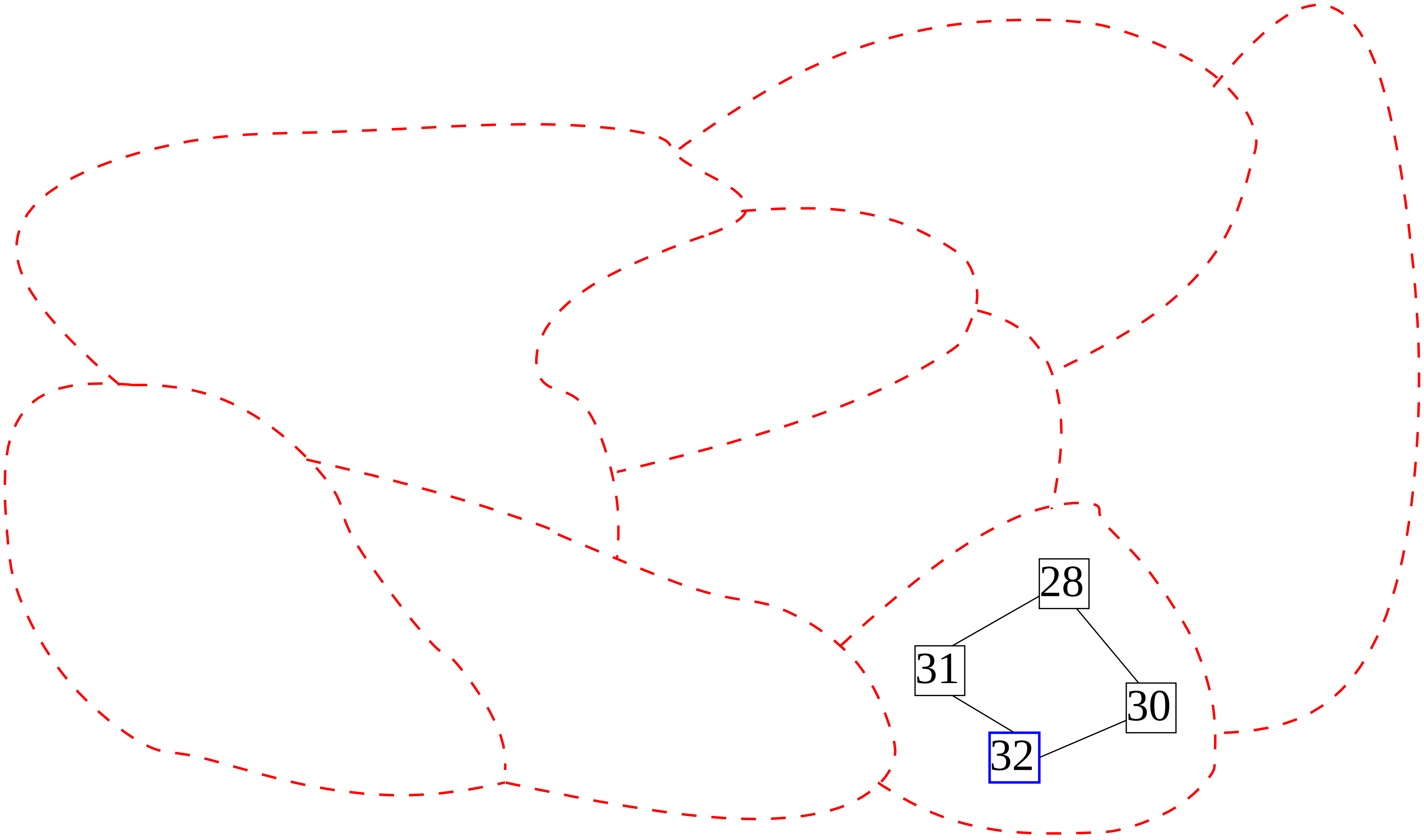

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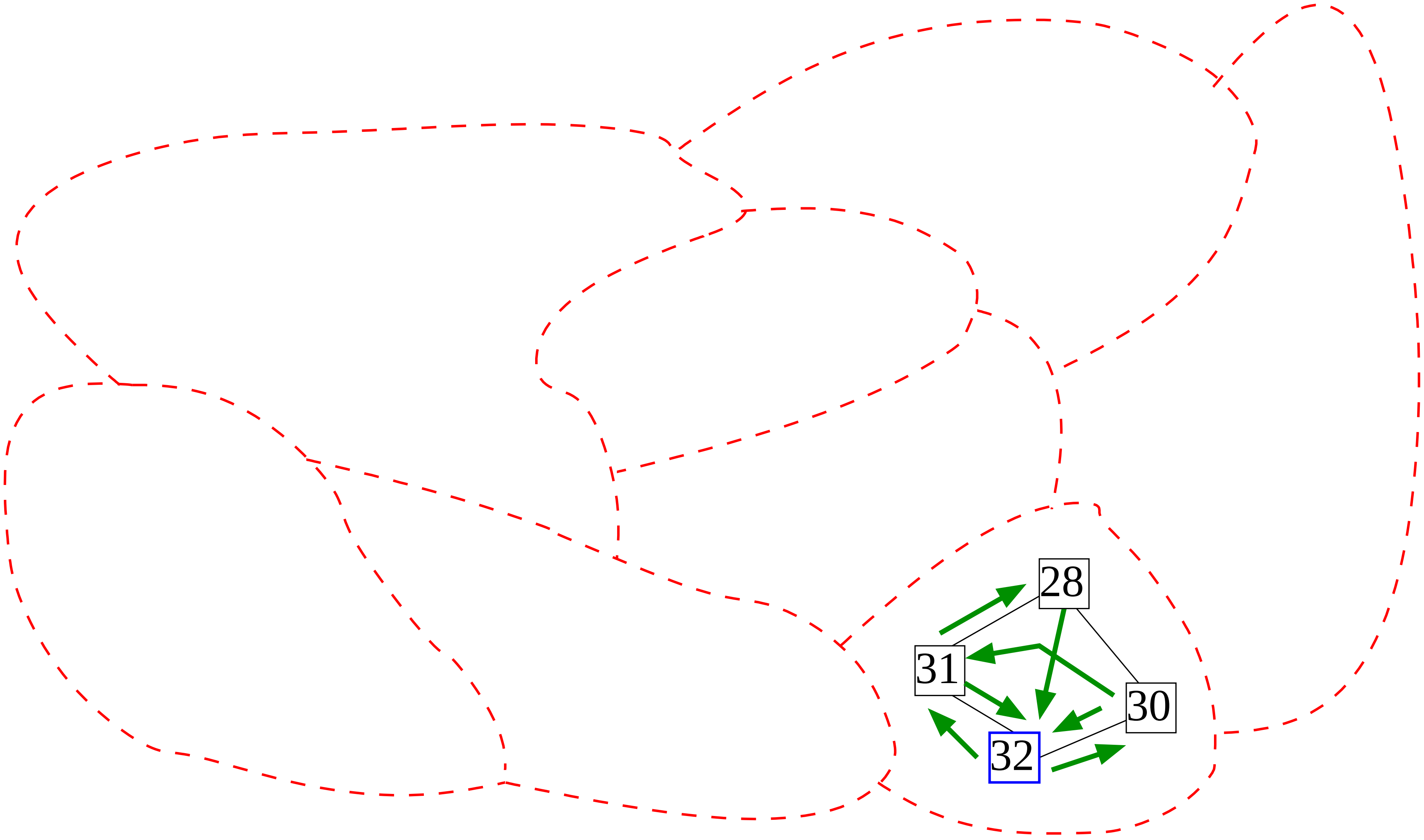
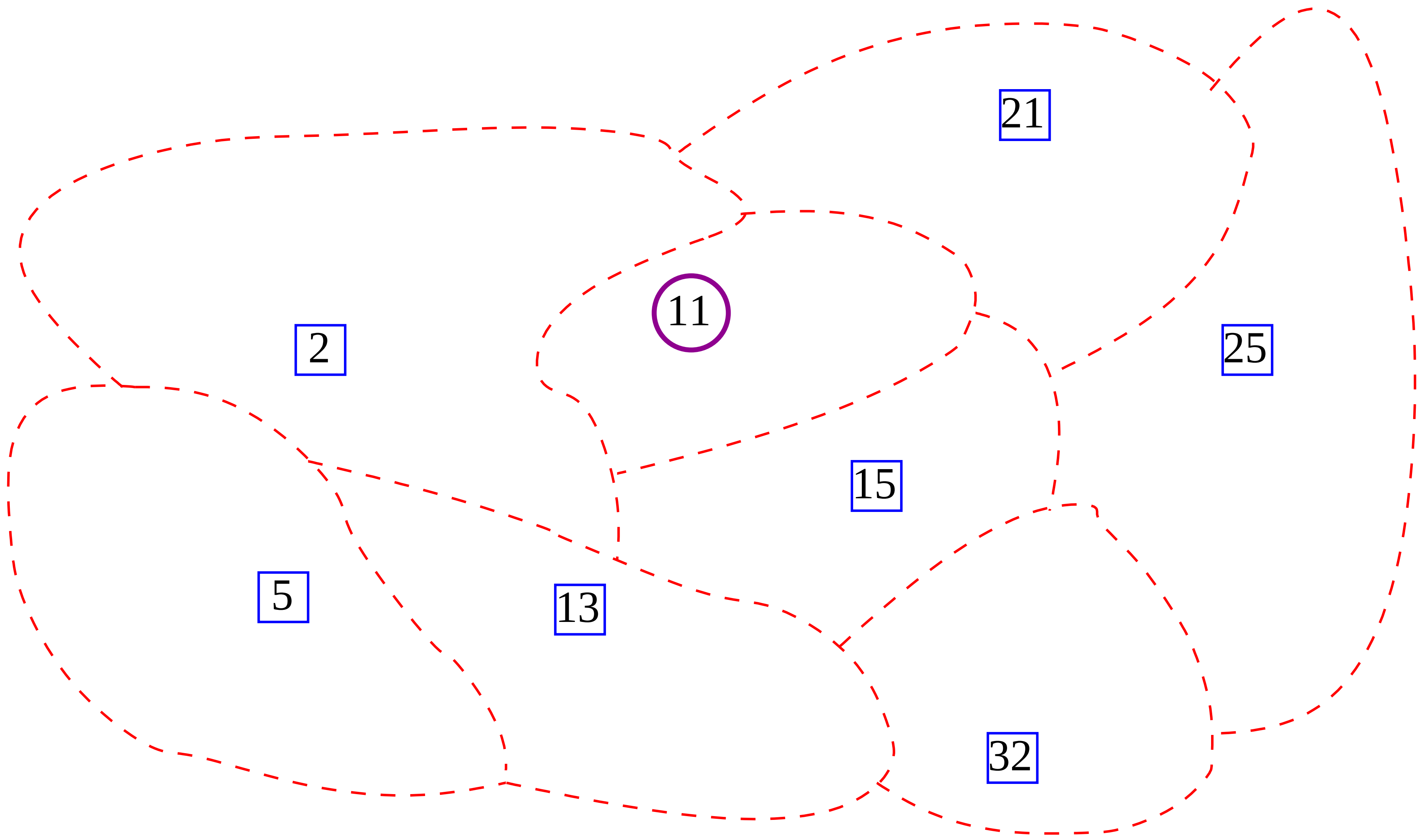


Illustration: Inter-Cluster Grooming



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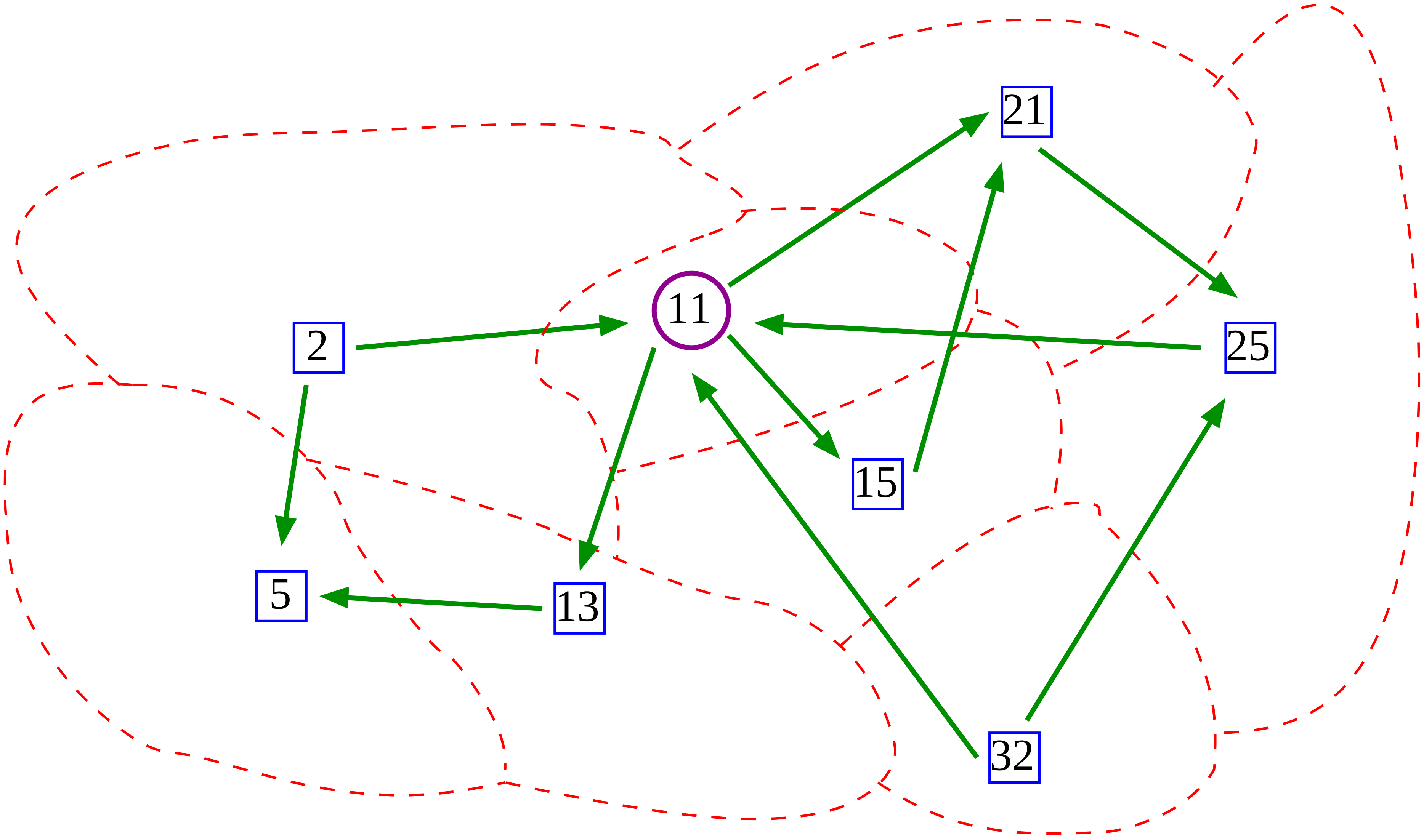


Benefits of Hierarchical Design

- Hierarchical control and management
- RWA on physical topology relatively independent of logical topology design
- Only hubs have grooming capability
- Effi cient handling of small traffi c components
- Limited number of electronic hops

Clustering and Hub Selection

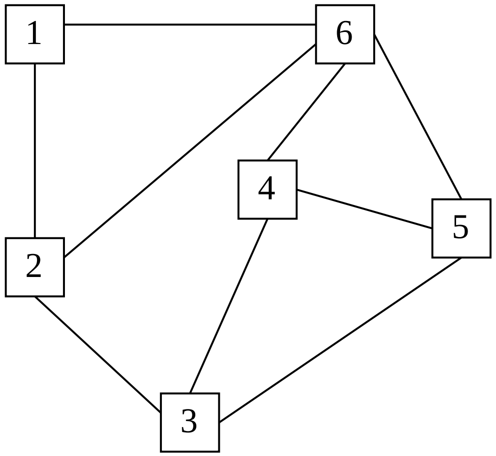
- Widely studied problem in network design and other domains
- Many algorithms exist, but do not address grooming considerations
- K-Center problem $\longrightarrow$ good match
  - minimizes max distance from any node to nearest center
  - does not take into account:
    - traffi c matrix
    - nodal 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 $\longrightarrow$ group nodes with dense traffi c
- Effect of cut links connecting to other clusters
- Physical shape of each cluster $\longrightarrow$ avoid linear topology
- Selection of hubs $\longrightarrow$ prefer high degree nodes

The “Virtual” Star Concept



- Any arbitrary topology

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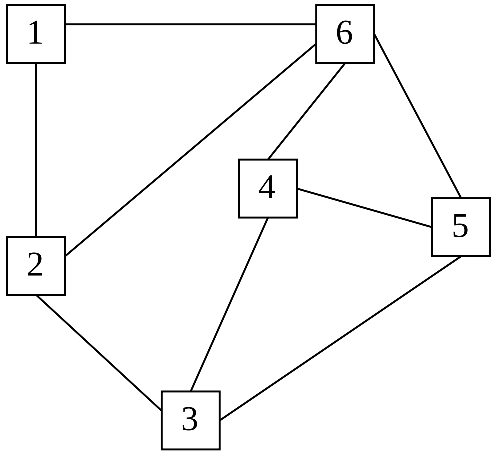

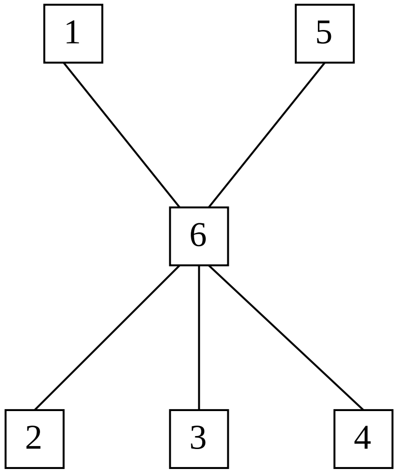

- Any arbitrary topology
- View as star to determine logical topology / traffi c routing

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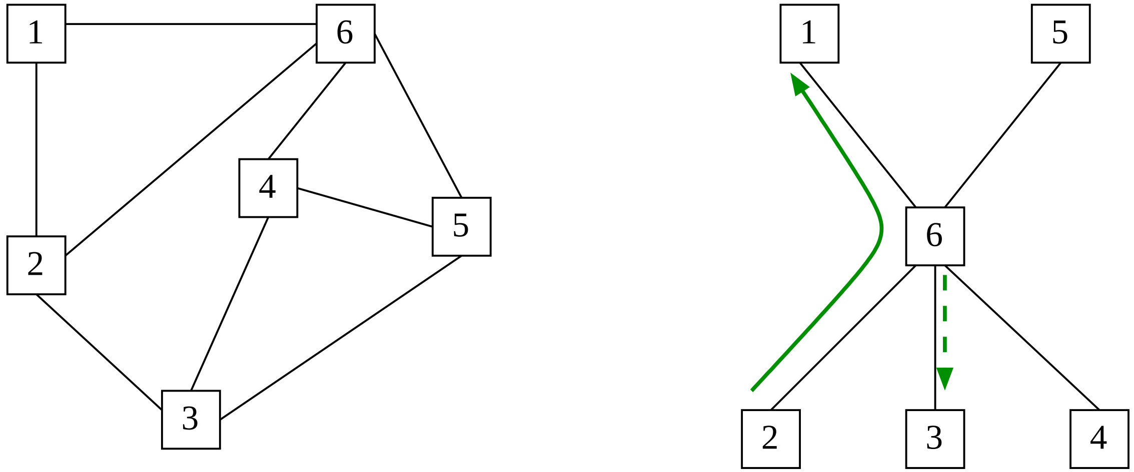

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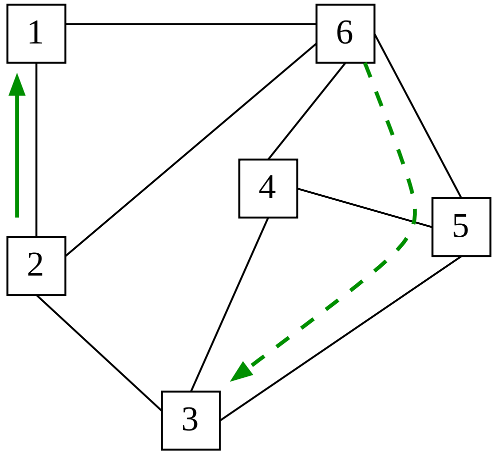

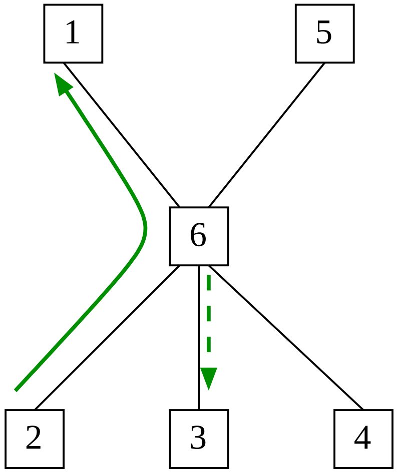

- Any arbitrary topology
- View as star to determine logical topology / traffi c routing
- Star topology not used for RWA
- Perform RWA on original topology

Computational Considerations

- Running time complexity:
  1. Clustering: $O(N^4)$
  2. Logical topology design and traffi c 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 traffi c demands
  - ILP relaxation
- Wavelength lower bound:
  - bisection of physical topology forms cut of size k with traffi c t going through $\longrightarrow$ bound $= t/kC$
  - used METIS tool to generate good cut
- Bounds independent of grooming method

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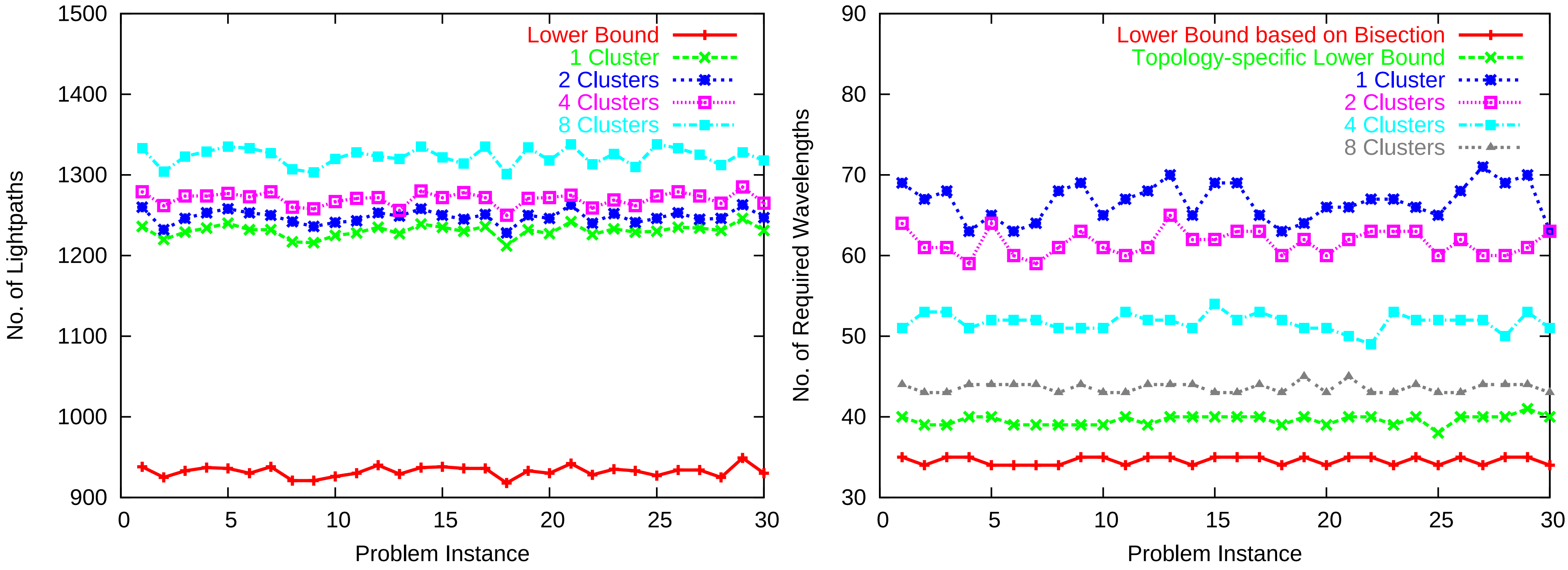
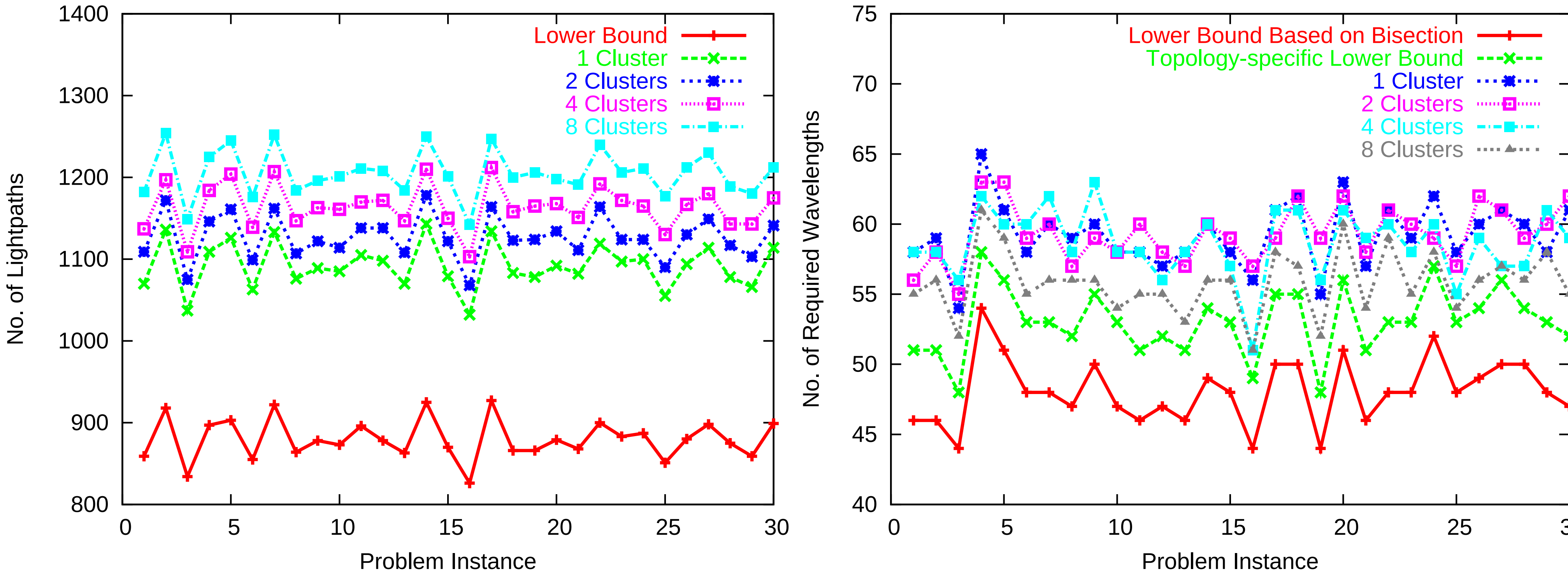
Results: 32-Node Network, Locality Traffic



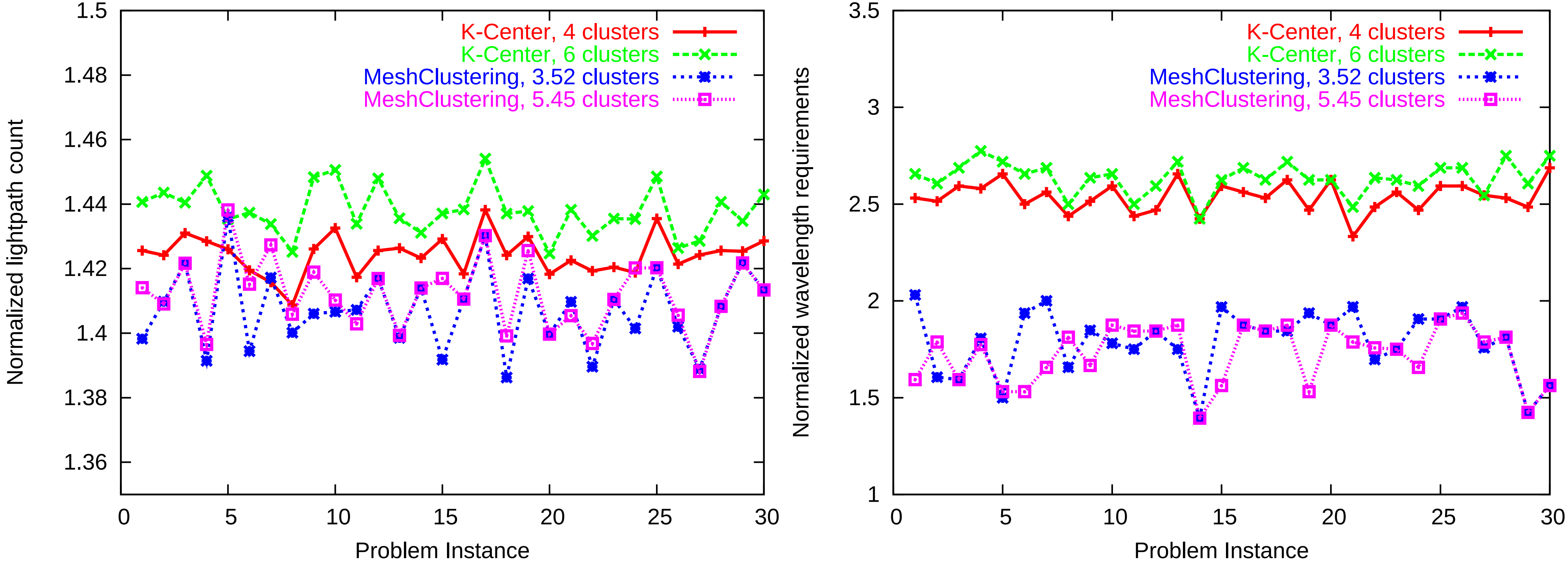
Results: 32-Node Network, Random Traffic



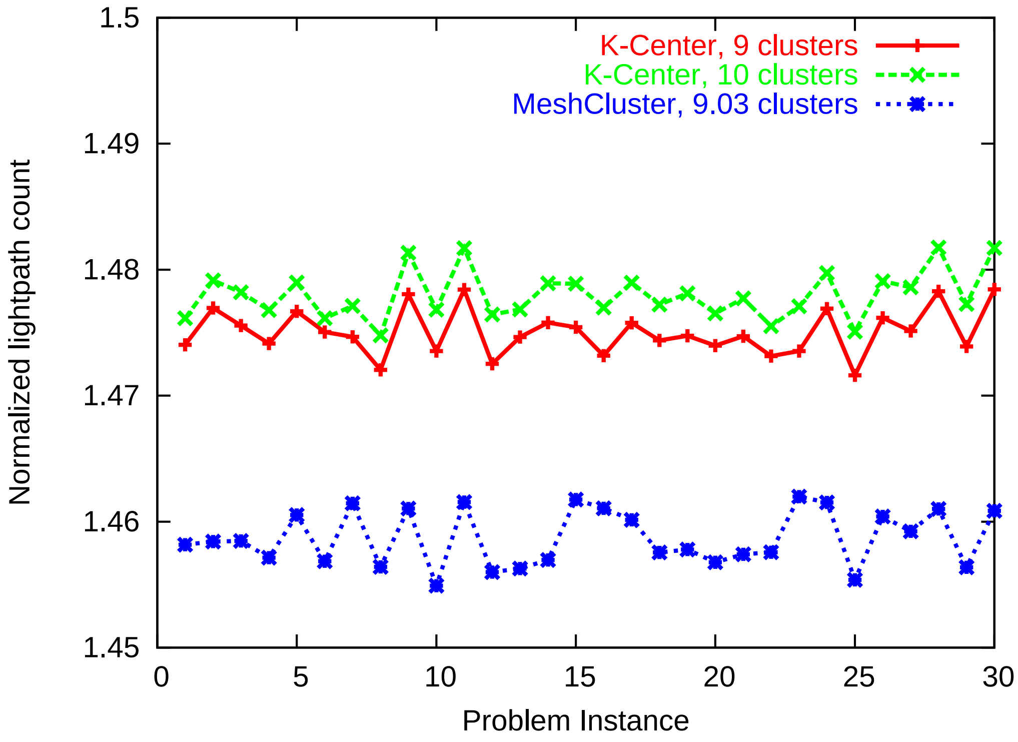
Results: 32-Node Network, Random Traffic

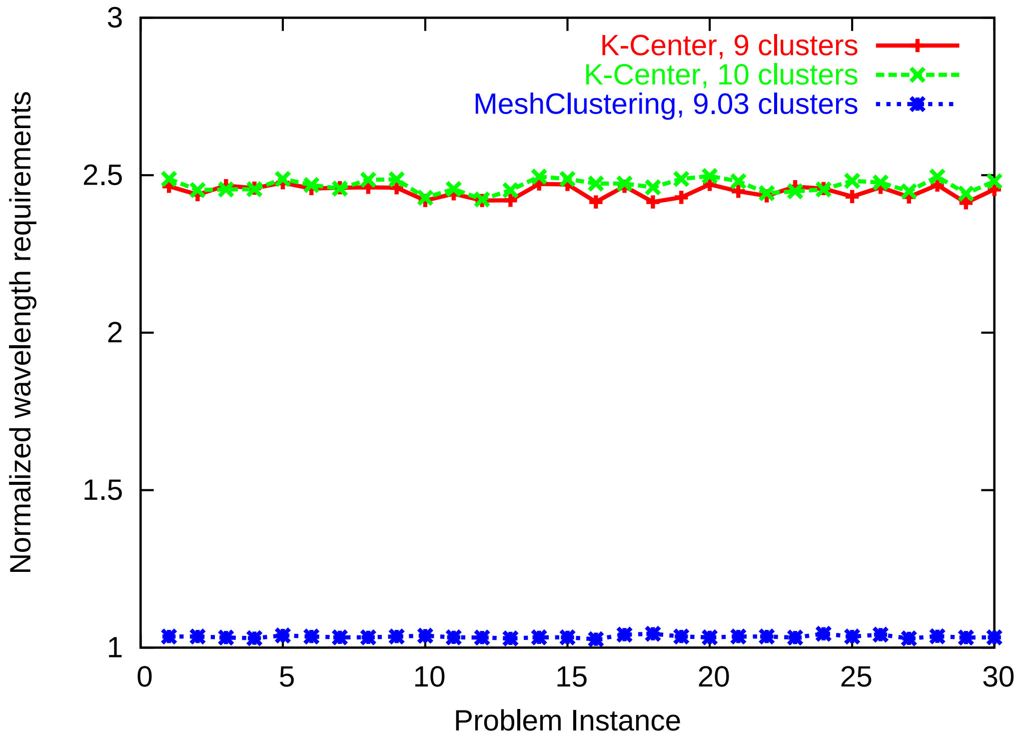
#Clusters	Avg LP Length	Avg Max Hub Degree	Wavelengths
1	3.17	266	60
2	3.07	228	60
4	2.93	183	59
8	2.84	143	56

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