# Scalable Traffic Grooming in Optical Networks

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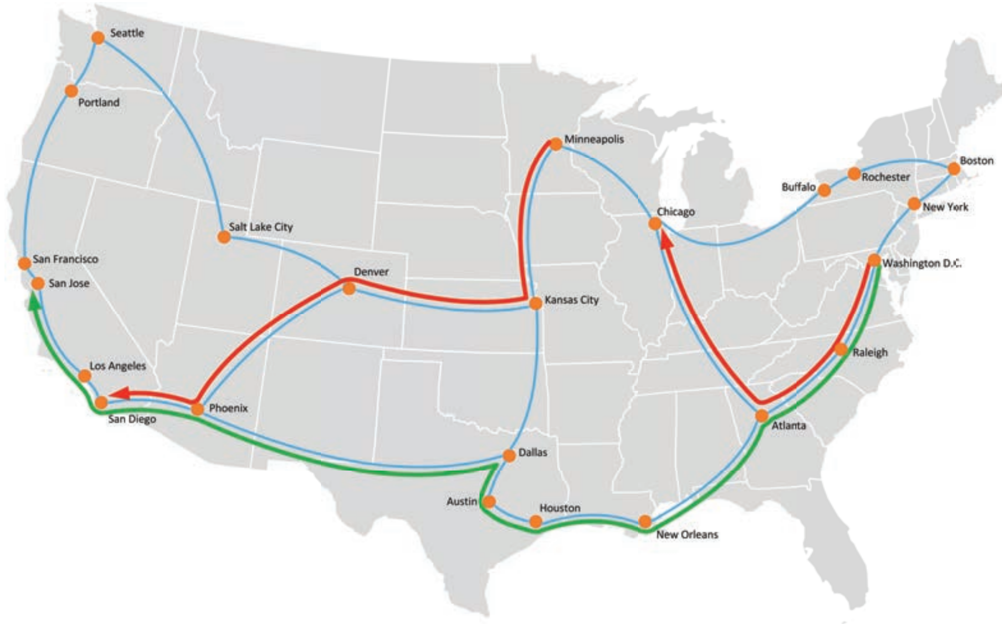
# Outline

- Motivation and Challenges
- Scalable Optical Network Design
  - Routing and Wavelength assignment (RWA)
  - Traffic Grooming
- Conclusion and Future Directions

# Optical Network Design




- Optical networks: the foundation of the global network infrastucture
- Network design and planning crucial to operation of the Internet:
  - QoS, support of critical applications
  - survivability to failures
  - economics
  - . . .

# Challenges

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- Optimal solutions do not scale with
  - network size
  - number of wavelengths ($\approx$ 100/fiber currently)

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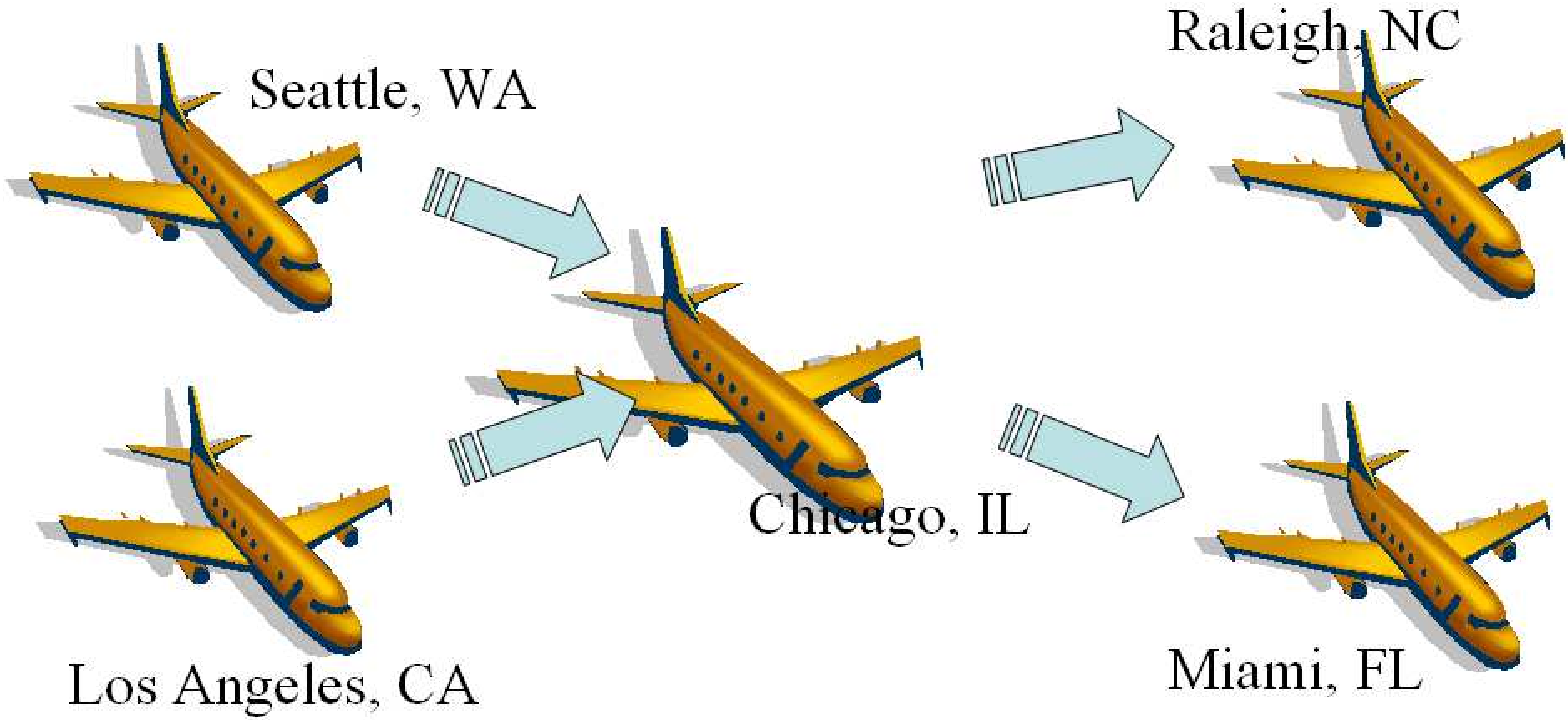
- Network design problems are hard
- Optimal solutions do not scale with
  - network size
  - number of wavelengths ($\approx$ 100/fiber currently)
- "What-if" analysis: substantial investments to explore sensitivity to:
  - forecast traffic demands
  - capital/operational cost assumptions
  - service price structures
  - $\cdots$

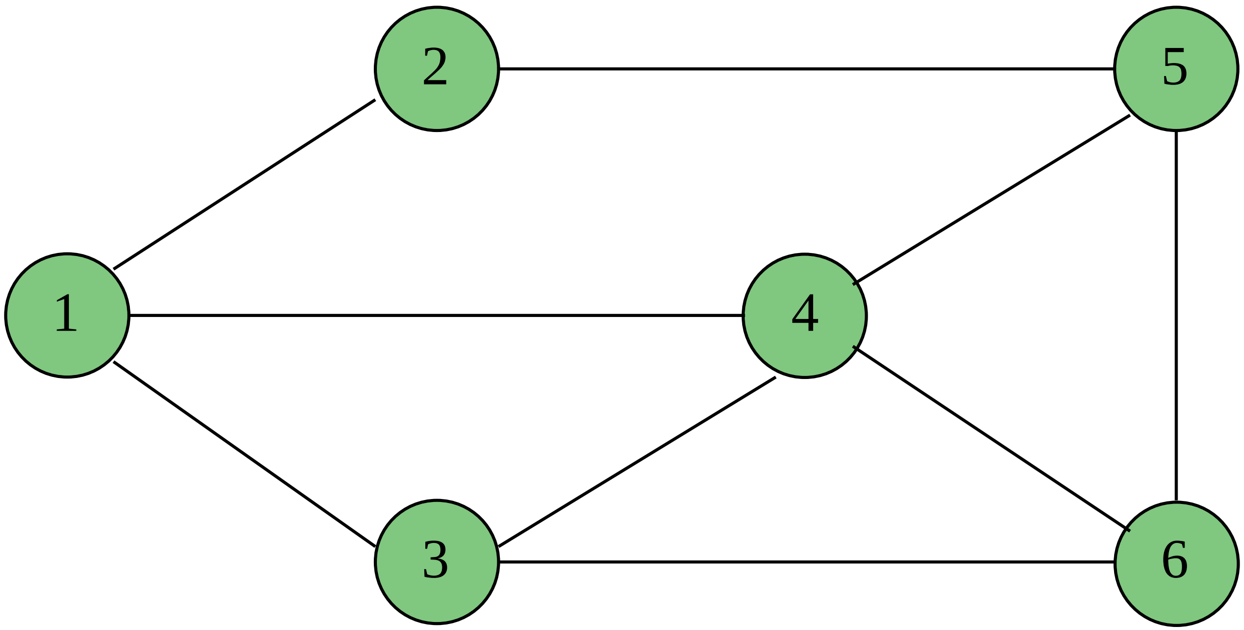
# Traffic Grooming: Airline Analogy



# Traffic Grooming as Optimization Problem

- Inputs to the problem:
  - physical network topology (fiber layout)
  - number of wavelengths $W$ and their capacity $C$
  - traffic matrix $T = [t_{sd}] \longrightarrow$ int multiples of unit rate (e.g., OC-3)
- Output:
  - logical topology
  - traffic grooming on lightpaths
  - lightpath routing and wavelength assignment (RWA)
- Objective:
  - minimize the number of lightpaths so as to carry the traffic

# Traffic Grooming Subproblems



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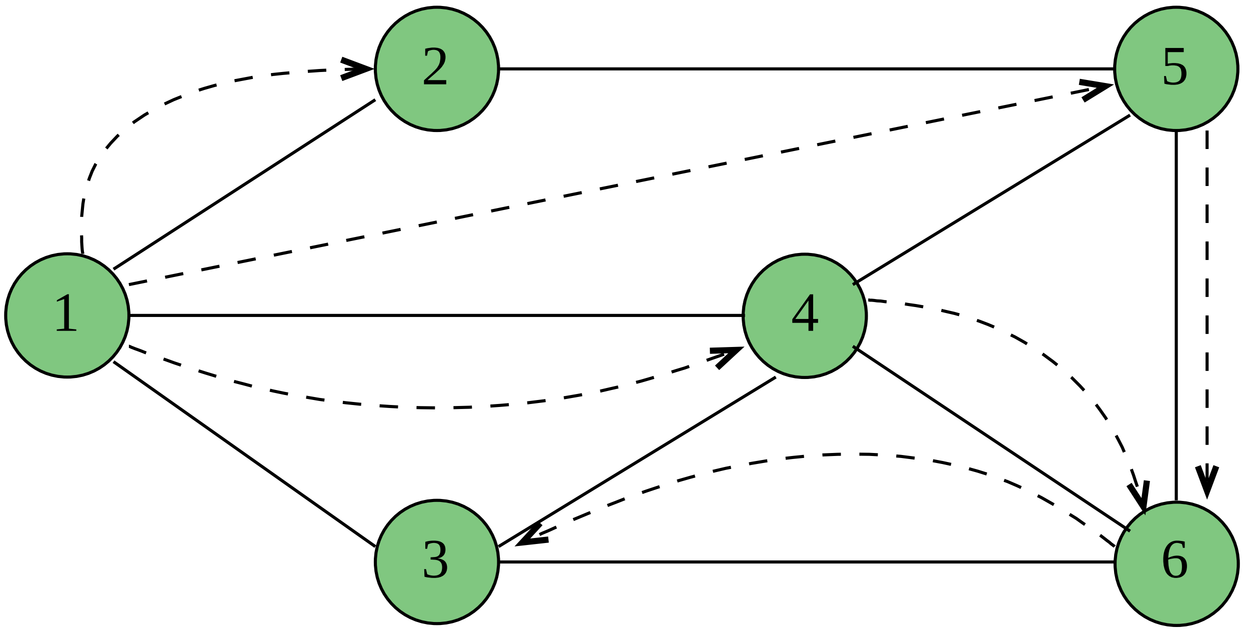


- Logical topology design → determine the lightpaths to be established

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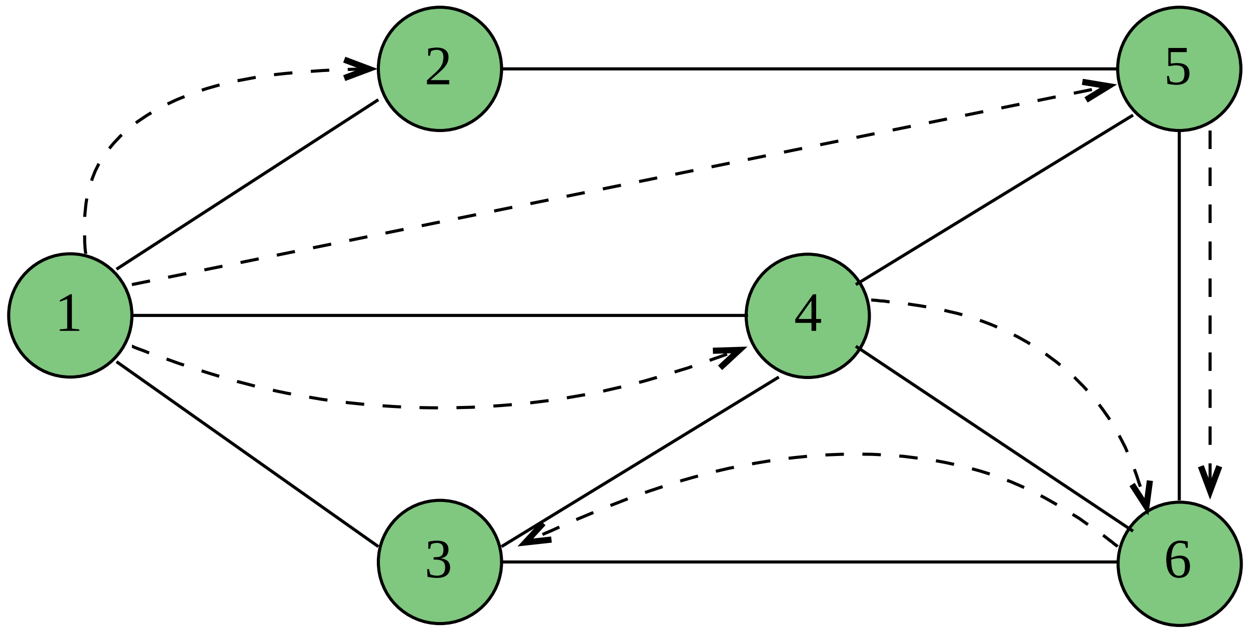


- Logical topology design $\longrightarrow$ determine the lightpaths to be established
- Traffic routing $\longrightarrow$ route traffic on virtual topology

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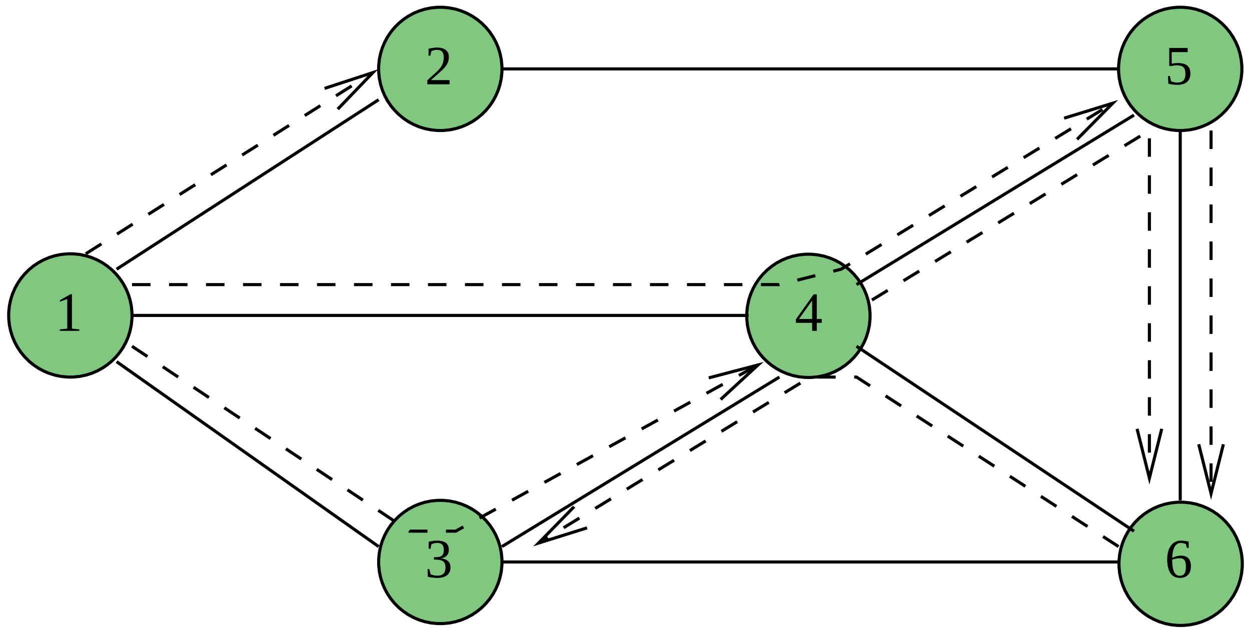
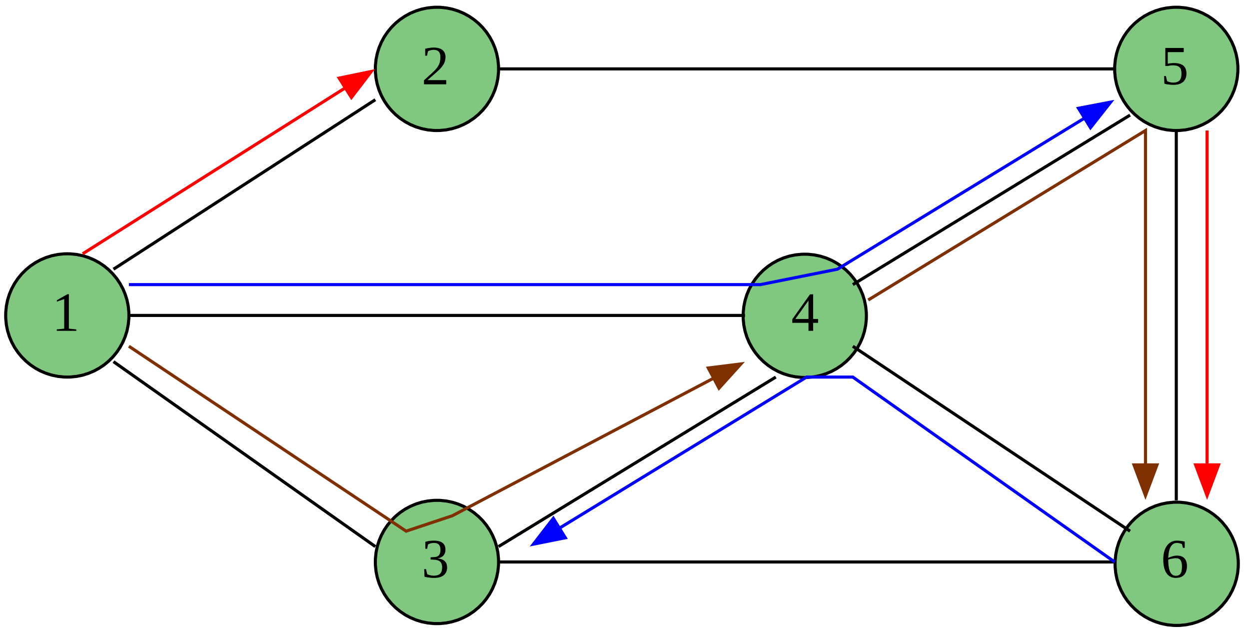


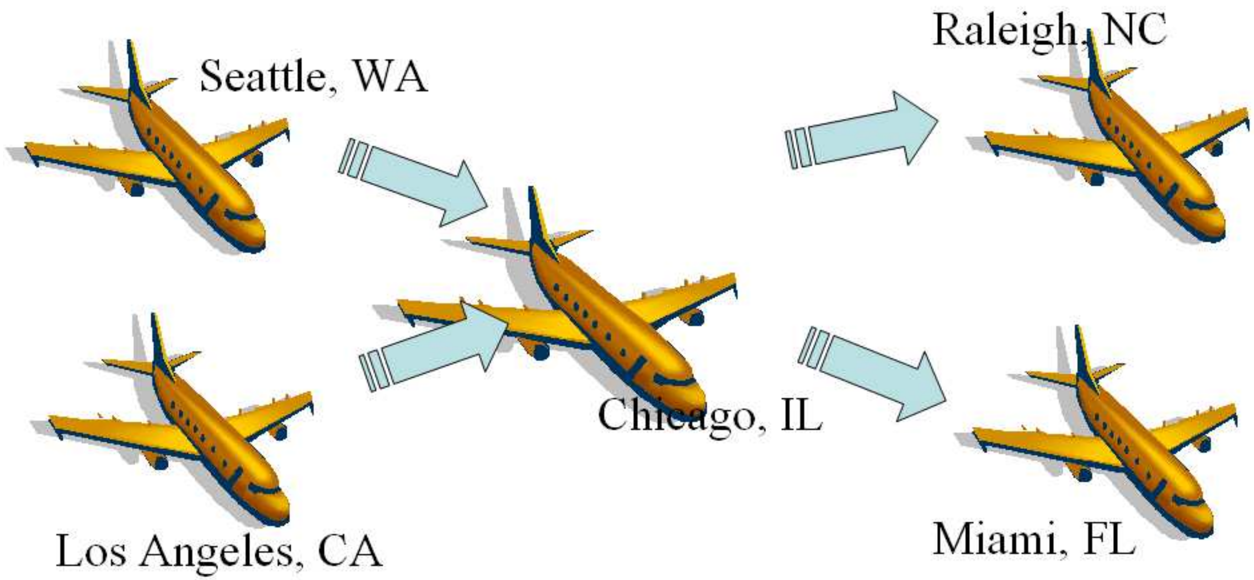

- Logical topology design ⟶ determine the lightpaths to be established
- Traffic routing ⟶ route traffic on virtual topology
- Lightpath routing ⟶ route the lightpaths over the physical topology

# Traffic Grooming Subproblems



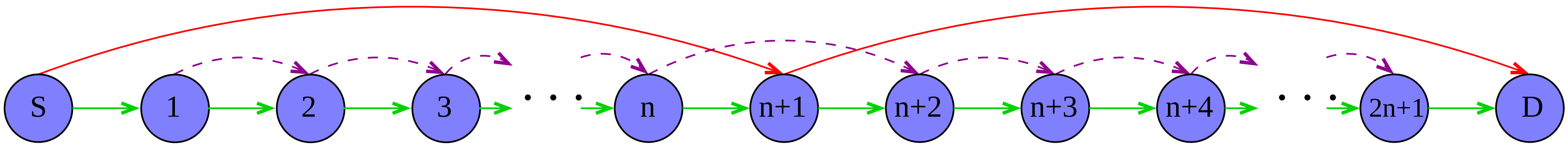

- Logical topology design $\longrightarrow$ determine the lightpaths to be established
- Traffic routing $\longrightarrow$ route traffic on virtual topology
- Lightpath routing $\longrightarrow$ route the lightpaths over the physical topology
- Wavelength assignment $\longrightarrow$ assign wavelengths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

# Airline Analogy (2)



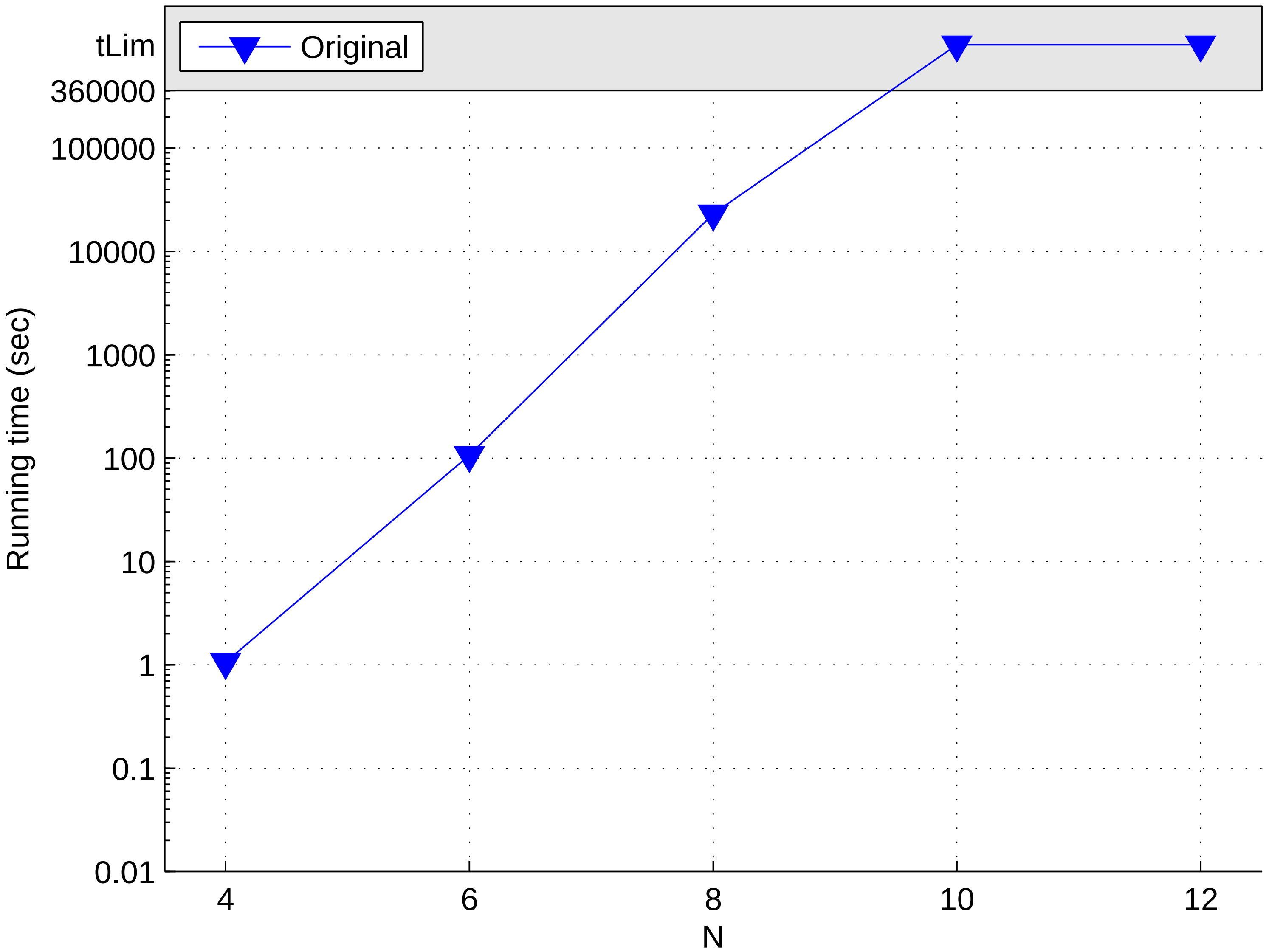

| | | |
|---|---|---|
| Lightpaths, logical topology | $\longleftrightarrow$ | Flights, flight routes |
| Traffic routing | $\longleftrightarrow$ | Travel itinerary |
| Electronic ports | $\longleftrightarrow$ | Gates |
| Grooming switch | $\longleftrightarrow$ | Hub airport |
| Wavelengths | $\longleftrightarrow$ | Gate timeslots |

# Traffic Grooming Complexity

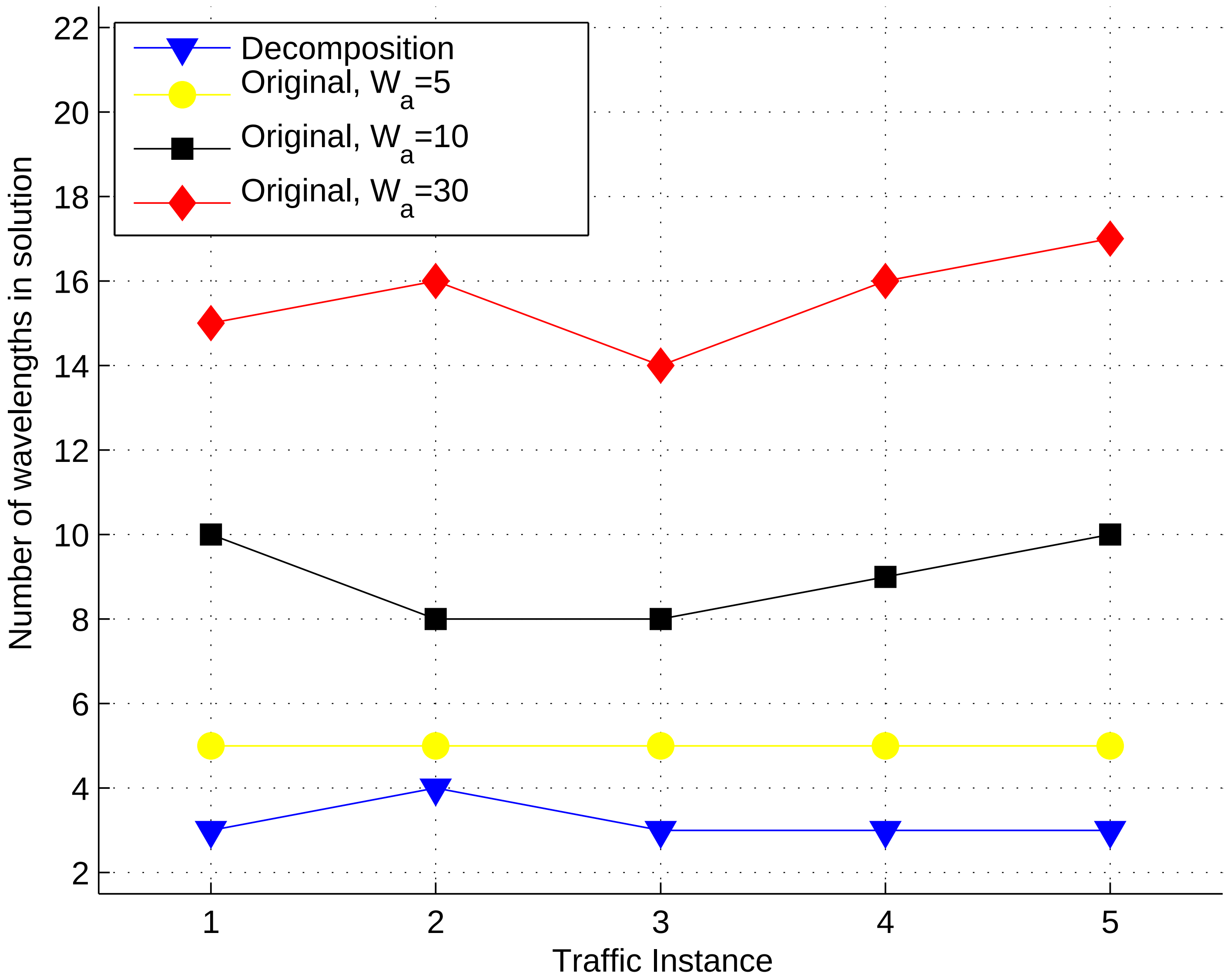



- Problem instance:
  - unidirectional linear (path) network
  - logical topology and RWA is given
  - traffic either bifurcated or not bifurcated
- Objective: find a routing of traffic onto the lightpaths
- Result: problem is NP-complete $\longrightarrow$ reduction from *Subset Sums*

# Challenge: Running Time



# Challenge: Wavelength Fragmentation



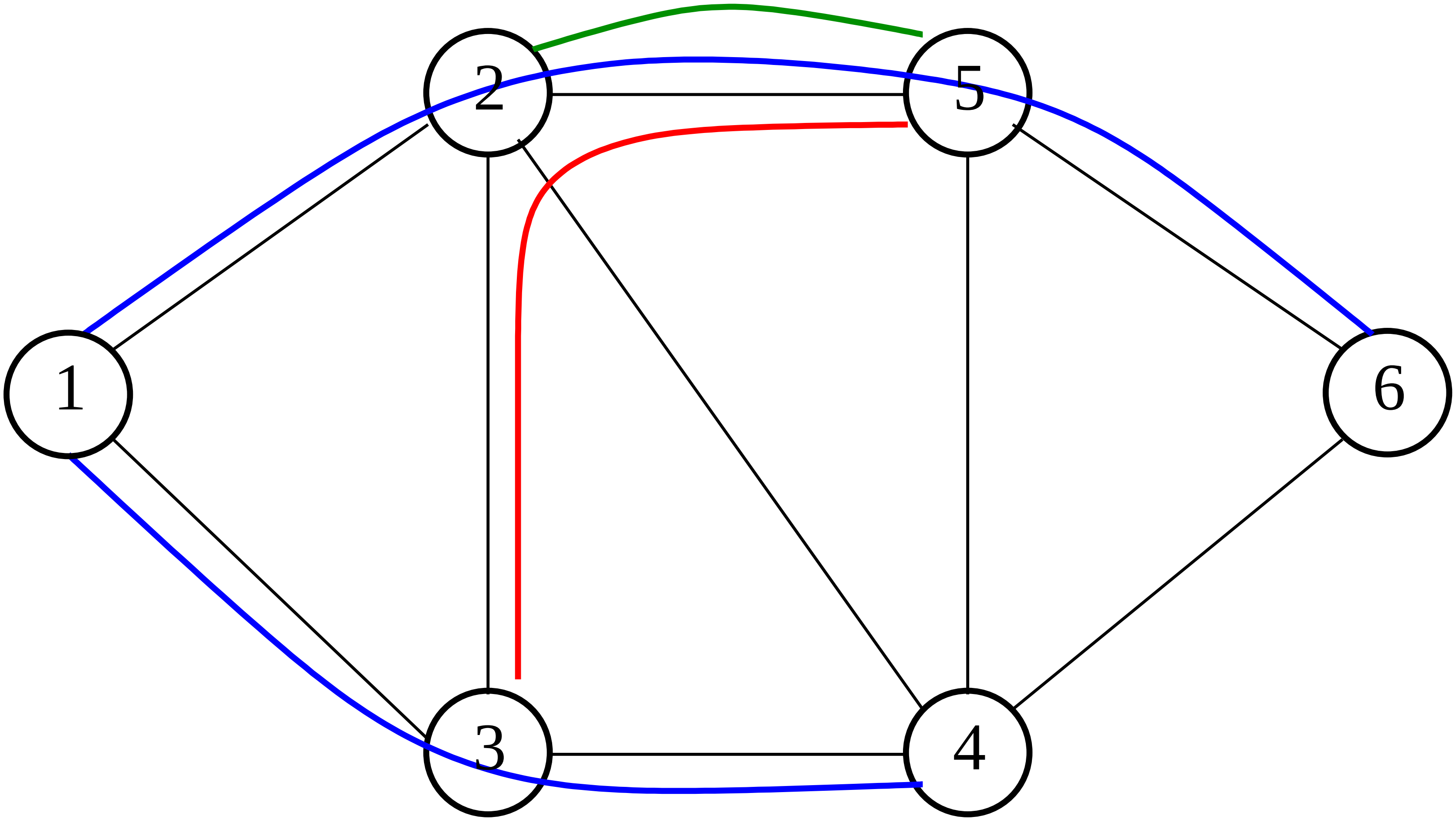
# Routing and Wavelength Assignment (RWA)

- Fundamental control problem in optical networks
- Objective: for each connection request determine a lightpath, i.e.,
  - a path through the network, and
  - a wavelength
- Two variants:
  1. online: lightpath requests arrive/depart dynamically
  2. offline: set of lightpaths to be established simultaneously

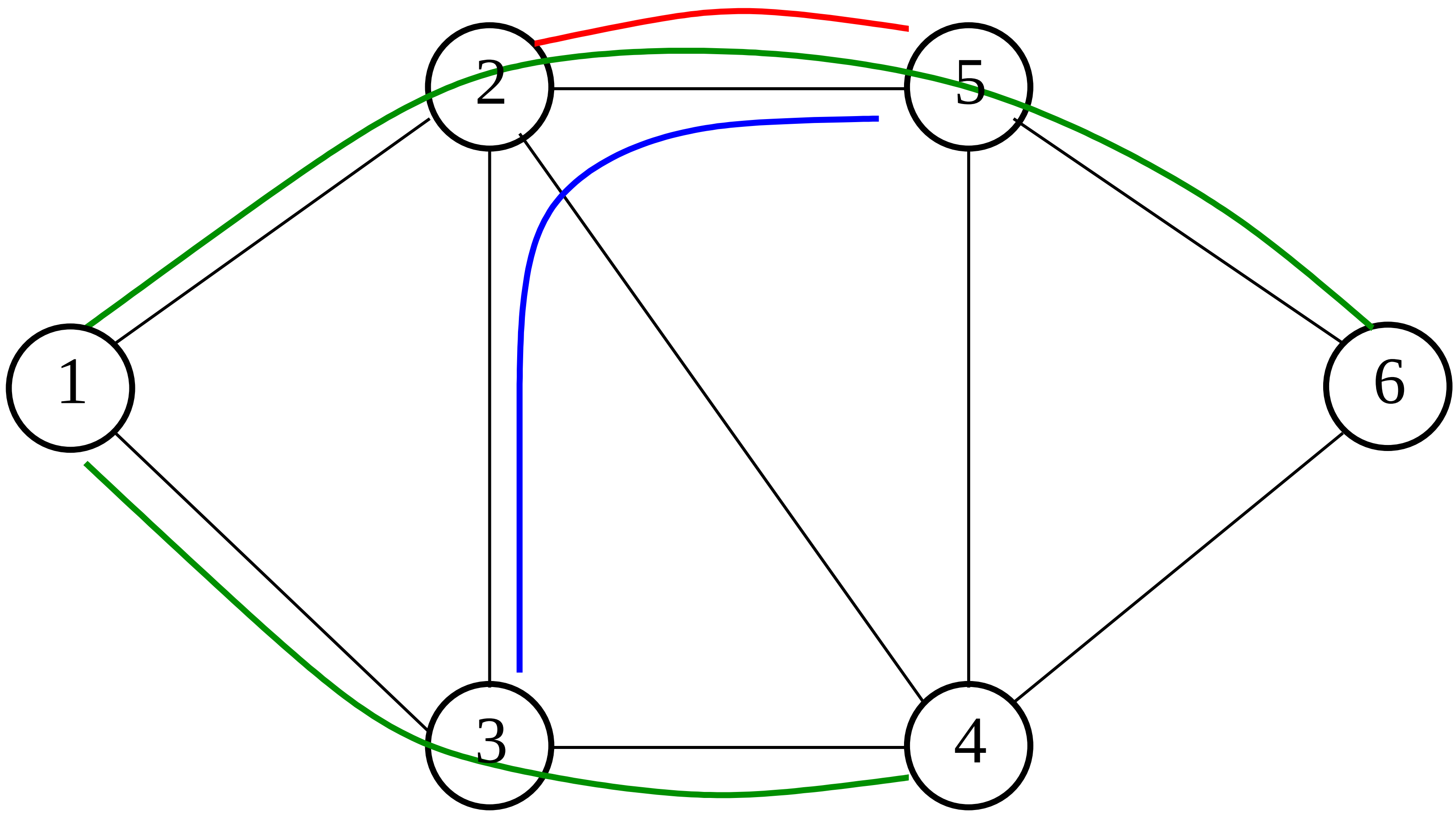
# Offline RWA

- Input:
  - network topology graph $G = (V, E)$
  - traffic demand matrix $T = [t_{sd}]$
- Objective:
  - establish all lightpaths with the minimum # of $\lambda$s
  - maximize established lightpaths for a given # of $\lambda$s
- Constraints:
  - each lightpath uses the same $\lambda$ along path
  - lightpaths on same link assigned distinct $\lambda$s
- NP-hard problem (both objectives)

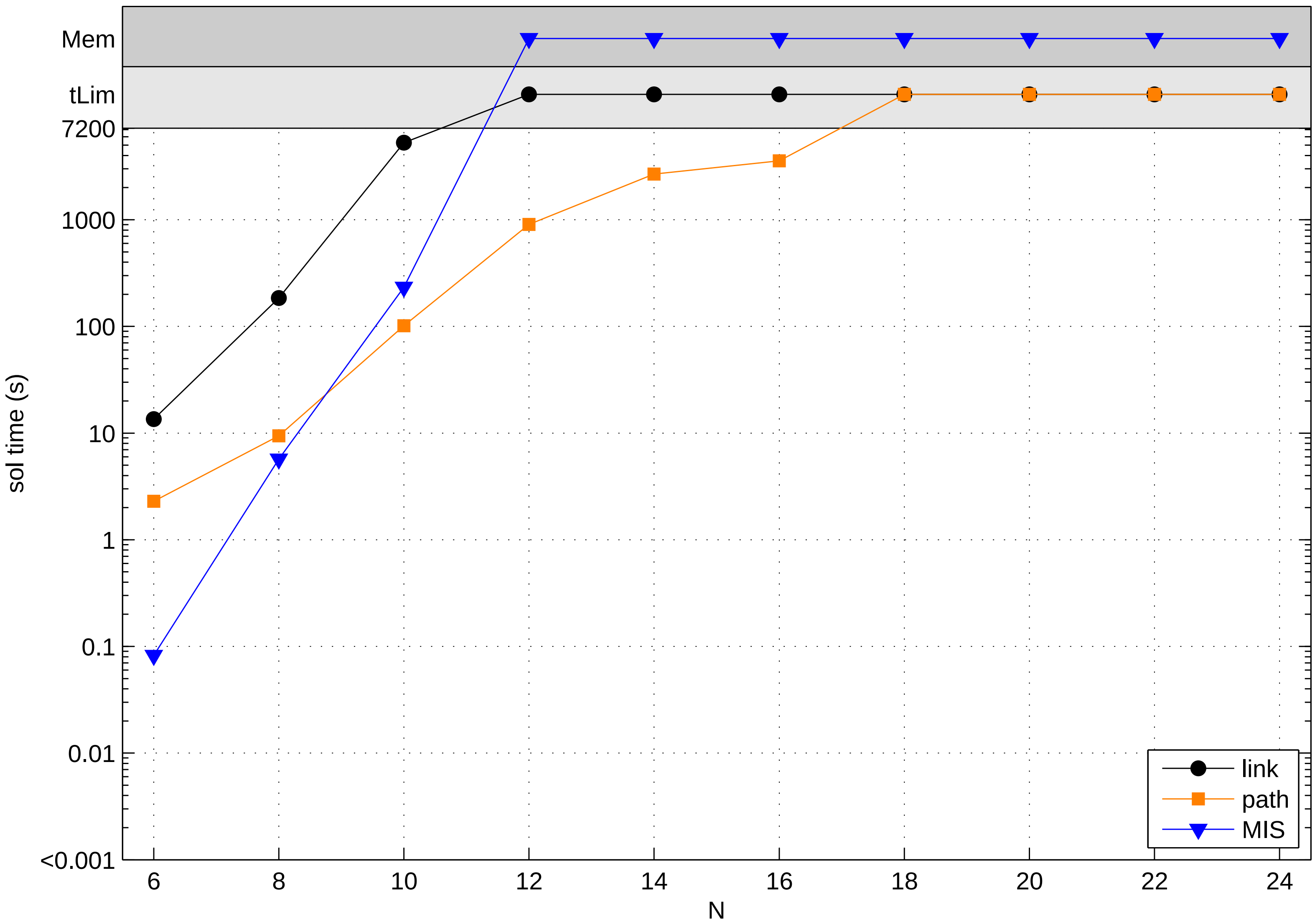
# RWA Example



# RWA: Symmetry



# Ring RWA: Running Time



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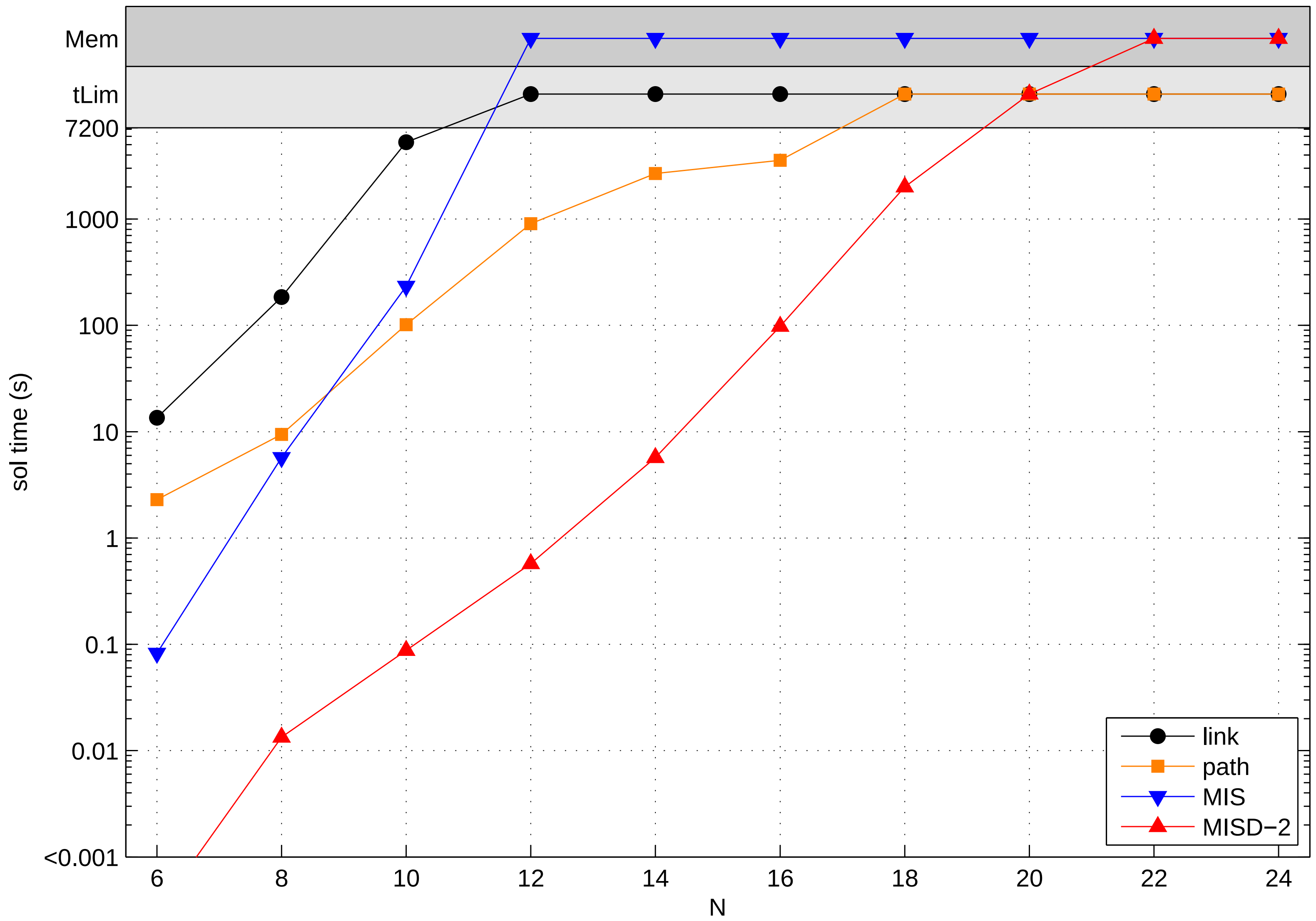

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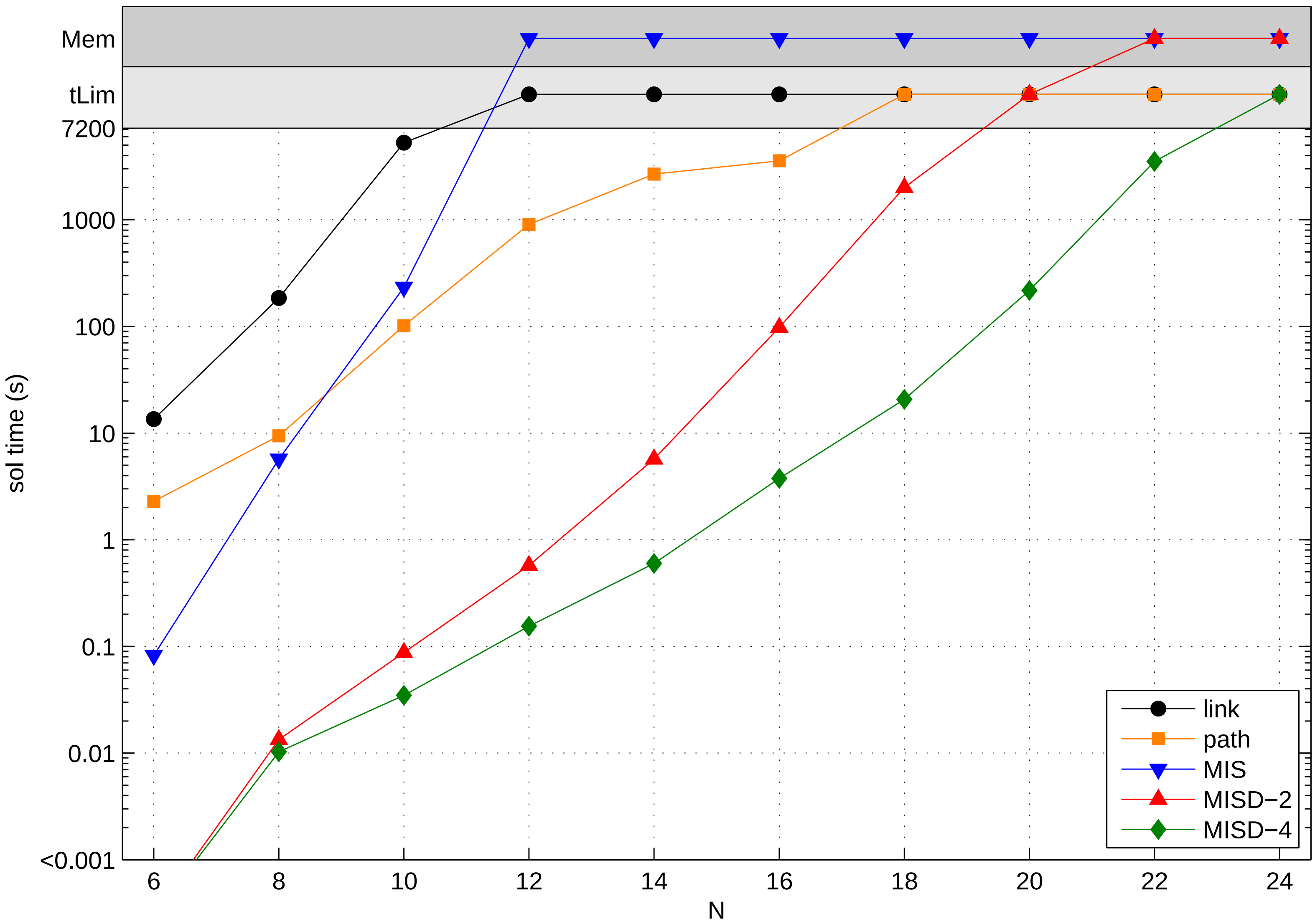

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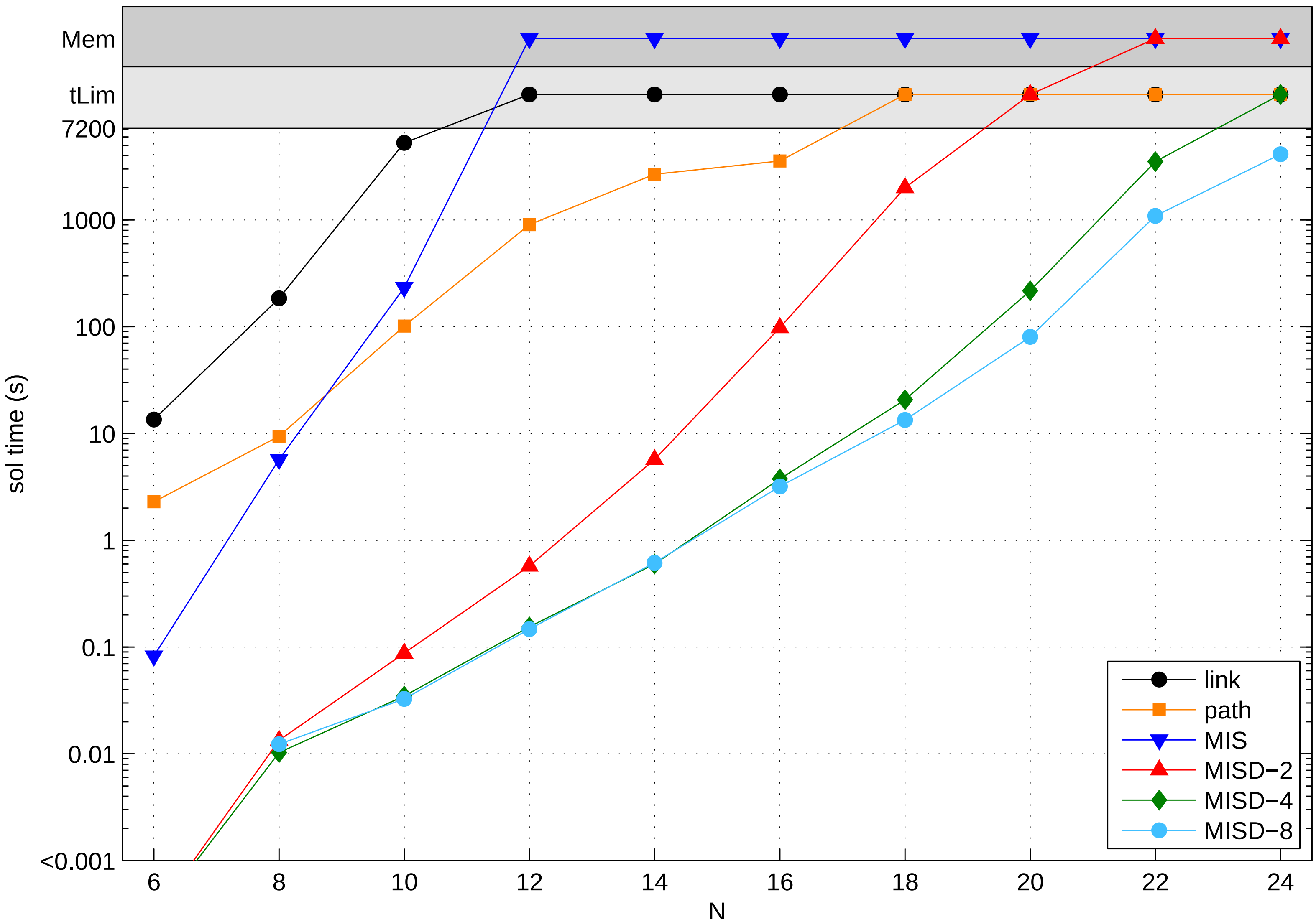
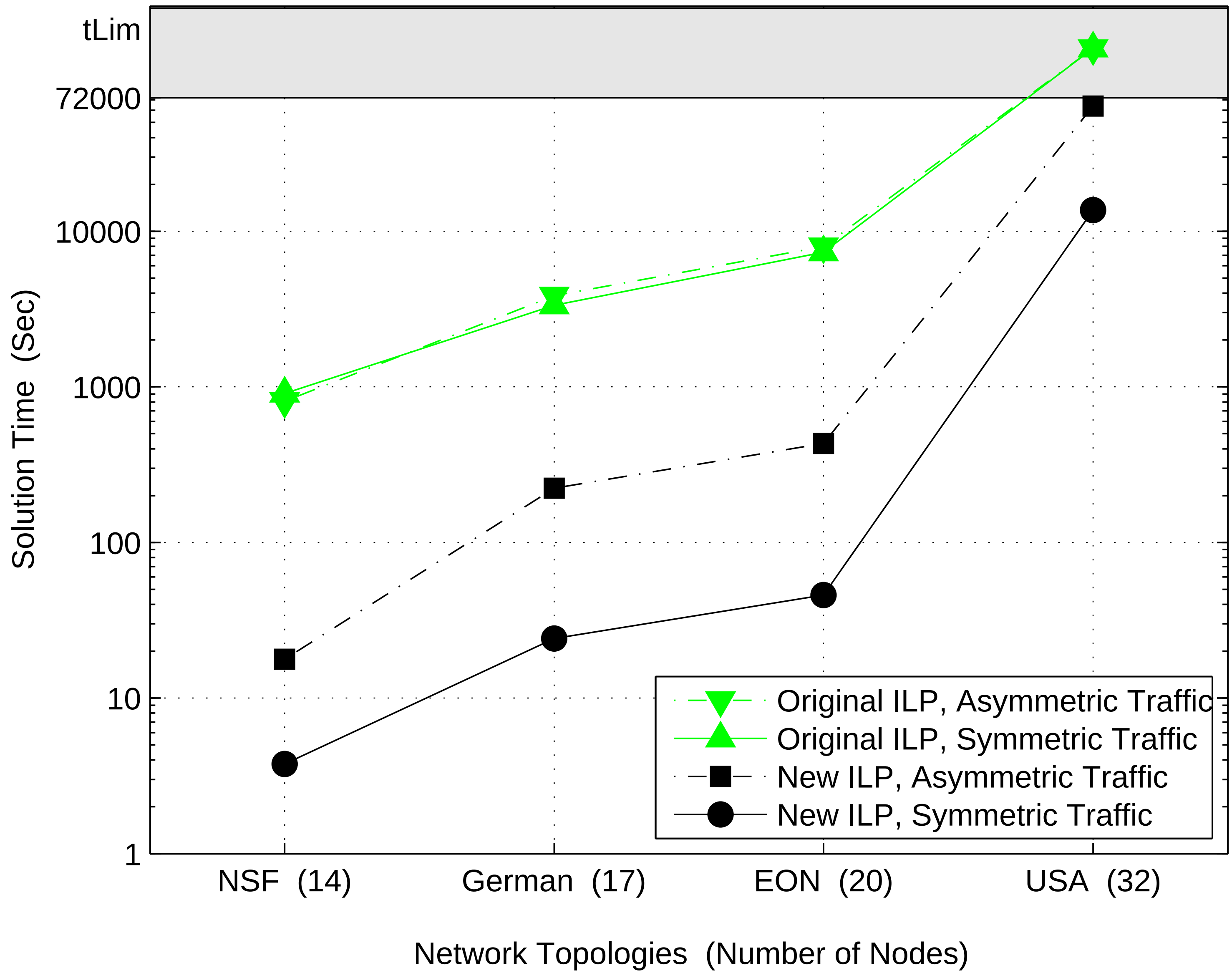


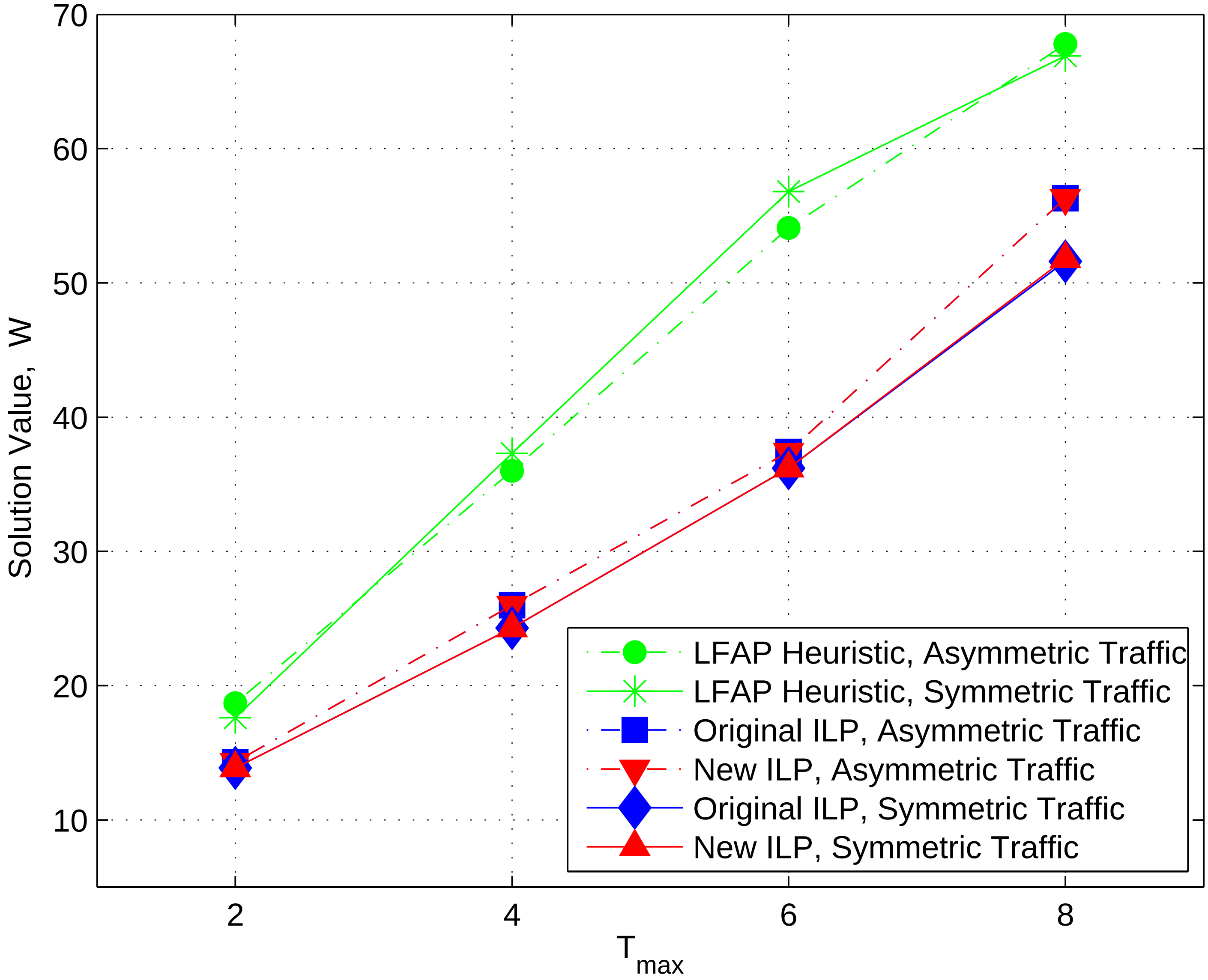
# Mesh RWA

- Path formulation:
  - compact formulation for optimal symmetric solutions
  - fast, close to overall optimal

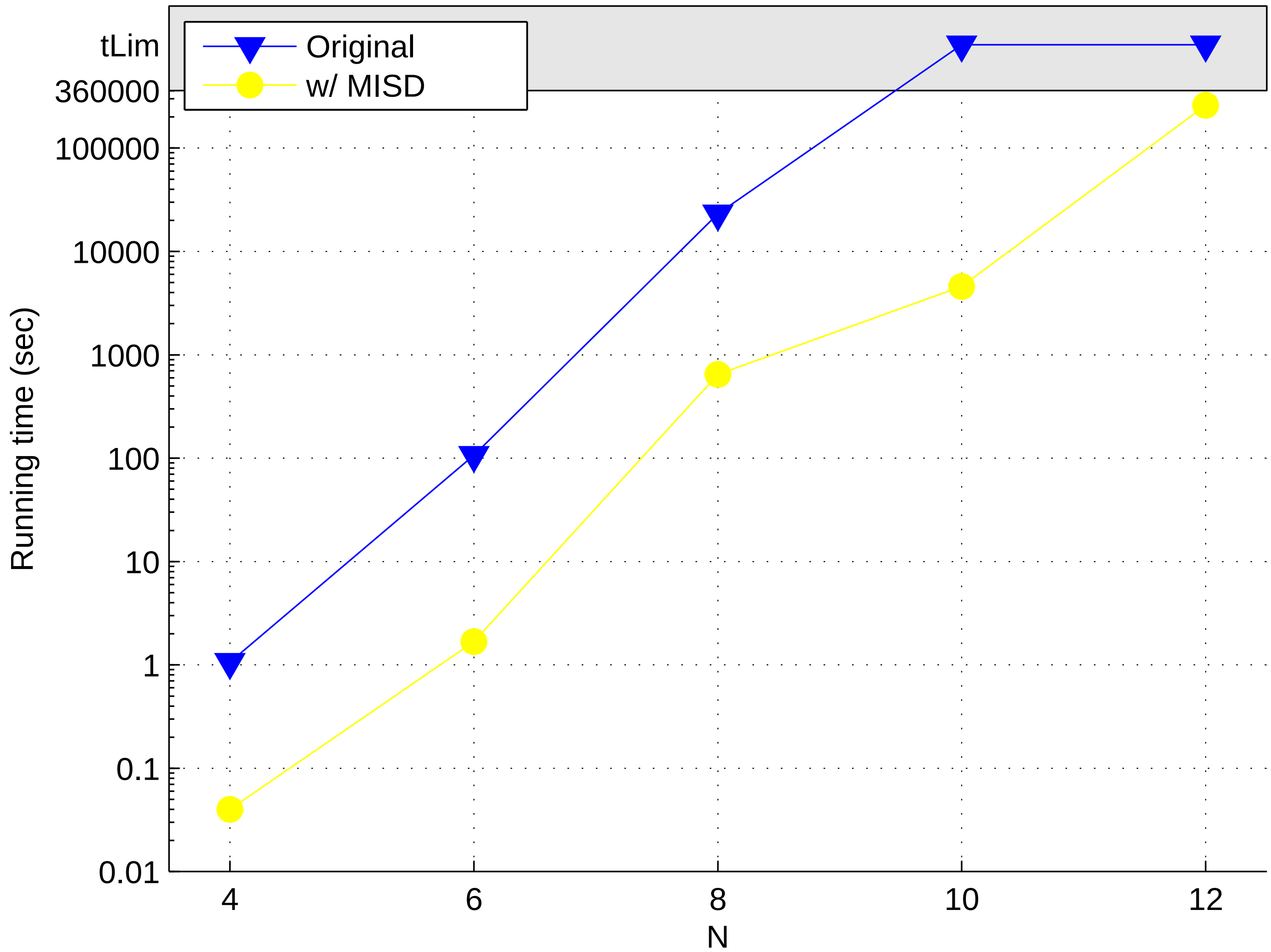
# Symmetric Solution: Running Time



# Symmetric Solution: Quality



# Traffic Grooming: Integrate MISD



# Traffic Grooming Decomposition

- Decompose and solve the two problems sequentially:
  1. Logical topology and traffic routing
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     - route and color lightpaths from Step 1
     - fast (for rings and medium mesh networks)

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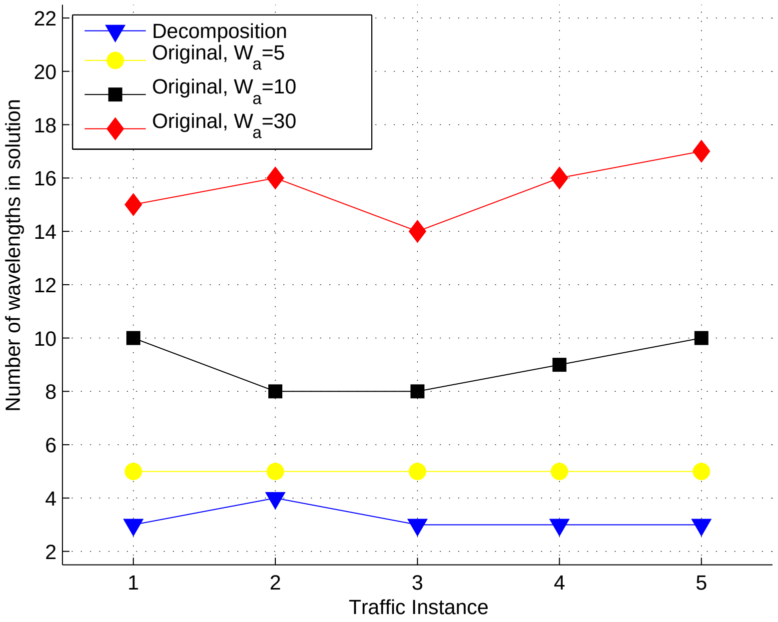
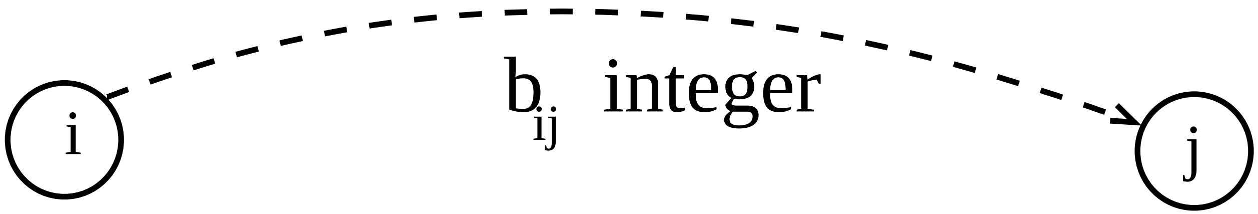
     - route and color lightpaths from Step 1
     - fast (for rings and medium mesh networks)
- Optimal for instances that are not $\lambda$-limited



# Logical Topology and Traffic Routing Problem

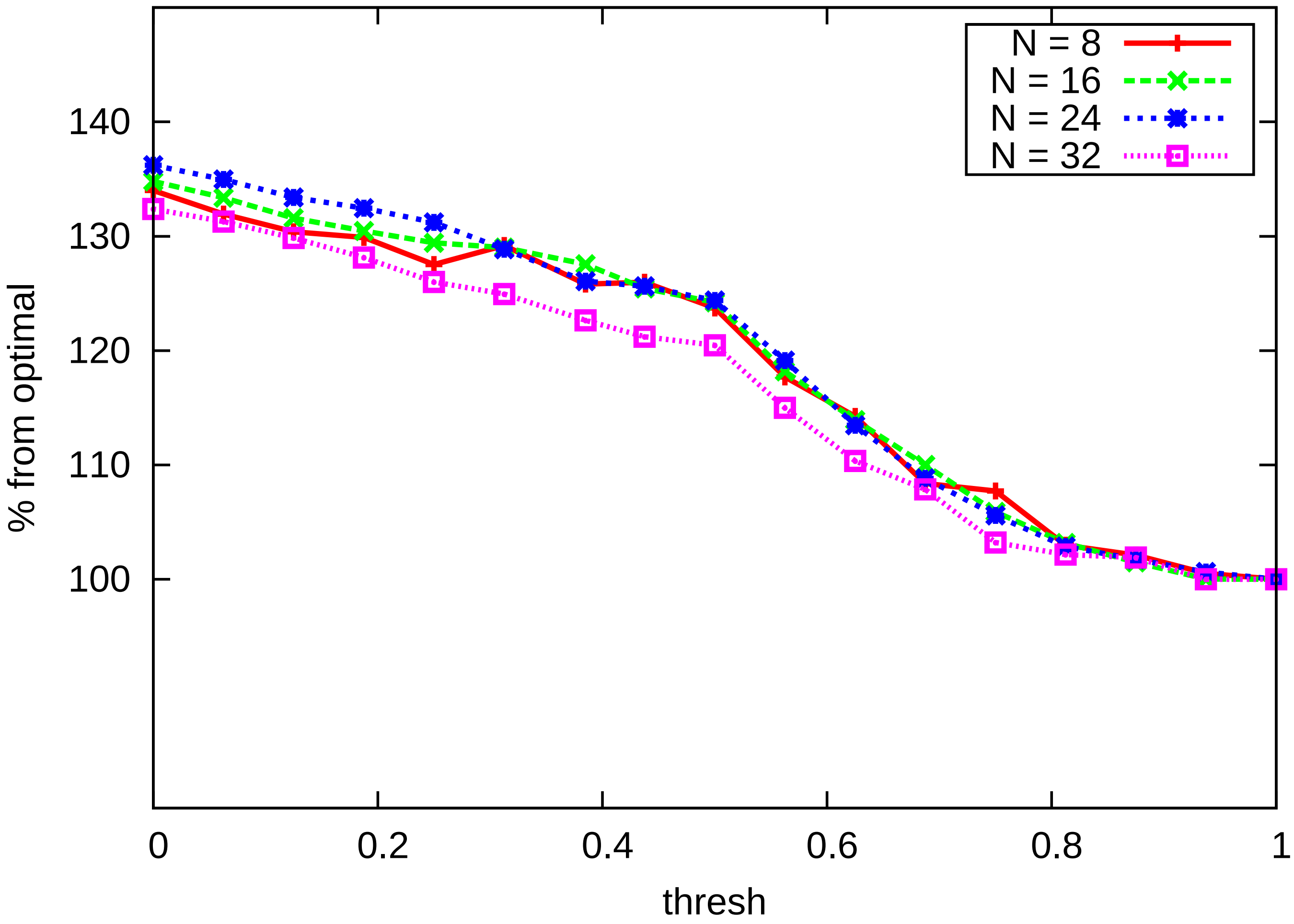



- Independent of physical topology
- Integer variables are not binary
  $\longrightarrow$ LP relaxation possible

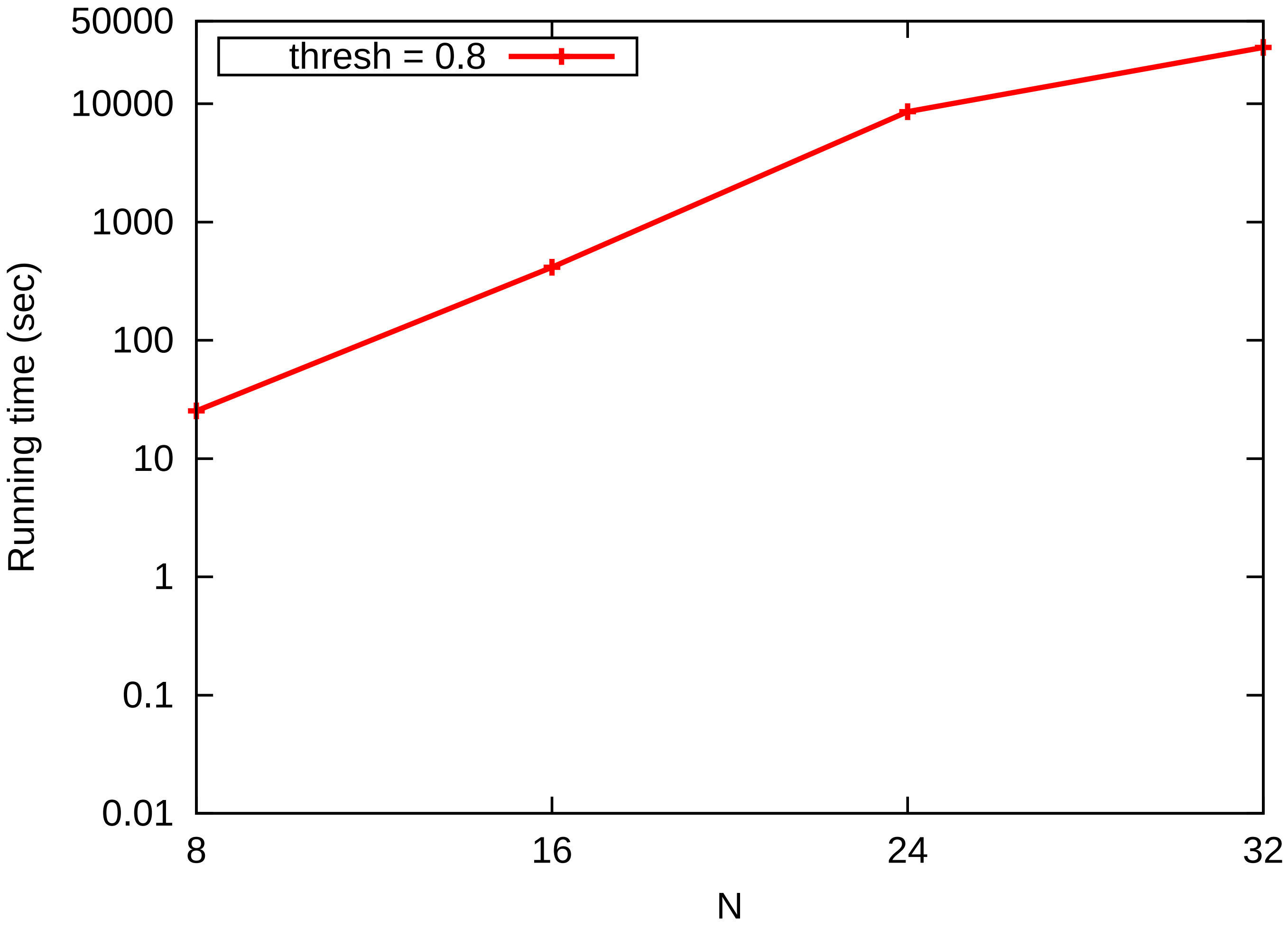
# Iterative Algorithm

1. $thresh \leftarrow 0$
2. Relax integrality constraints on lightpath variables s.t.:
   $b_{ij} - \lfloor b_{ij} \rfloor > thresh$
3. Solve relaxed problem
4. If all variables integer, stop
5. If $thresh > .8$, stop
6. $thresh \; += \; 1/C$
7. Repeat from Step 2

# Iterative Algorithm: Quality



# Iterative Algorithm: Running Time



# Conclusion & Ongoing Research

- First steps towards efficient network design
  - scalable techniques on commodity hardware
  - lower the barrier to entry
  - focus on exploring design options, not ILP details

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- First steps towards efficient network design
  - scalable techniques on commodity hardware
  - lower the barrier to entry
  - focus on exploring design options, not ILP details
- Many open problems:
  - impairment-aware RWA
  - shared protection, survivable grooming
  - routing and spectrum allocation in elastic optical networks