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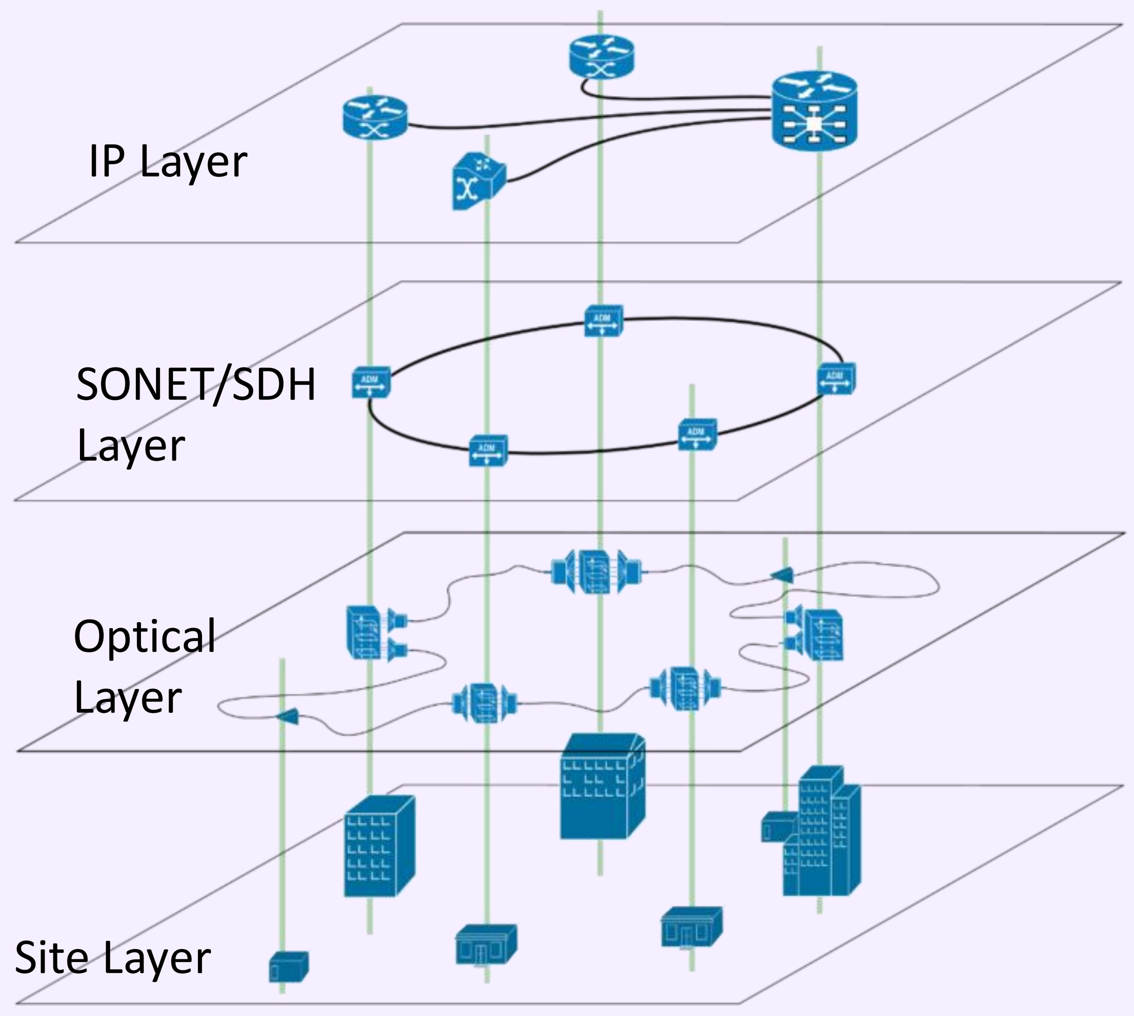
Integer Linear Programming Modeling for Multi-layered Network Optimization Problems

Background & Objectives

- Deployment of multiple technologies brings challenges to the design and operation of networks.
- Partitioning networks into layers can help simplify the network design and provide flexibility to upgrade the networks.
- The complexity resulting from this layering design requires an effective optimization model to support cost-effective resource provisioning.



Methodology

- Two Integer Linear Programming (ILP) formulations are provided for multi-layered network optimization problems:

  ***1. Link-Path ILP Formulation* (LPIF)**
  ***2. Node-Link ILP Formulation* (NLIF)**

Link-Path ILP Formulation

Minimize:

$$\sum_{l}\sum_{e} \xi_l \cdot M_{e,l} + \sum_{e} T \cdot P_{e,1} \cdot M_{e,1}$$

Demand Constraint:

$$\sum_{p^l} F^l_{e^{l+1}p^l} = Y^{l+1}_{e^{l+1}}$$

Capacity Constraint:

$$\sum_{e^{l+1}}\sum_{p^l} \delta^l_{e^l e^{l+1} p^l} \cdot F^l_{e^{l+1}p^l} \le Y^l_{e^l}$$

$$Y^l_{e^l} \le M_{e,l} \cdot C_l$$

Node-Link ILP Formulation

Minimize:

$$\sum_{l}\sum_{m,n} \xi_l \cdot M_{mn,l} + \sum_{m,n} T \cdot P_{mn,1} \cdot M_{mn,1}$$

Flow Conservation Constraints:

$$\sum_{n} F^{ij}_{in,l} = \sum_{m} F^{ij}_{mj,l} = Y_{ij,l+1}$$

$$\sum_{n} F^{ij}_{nt,l} = \sum_{m} F^{ij}_{tm,l}$$

Capacity Constraints:

$$\sum_{i,j} F^{ij}_{mn,l} = Y_{mn,l}$$

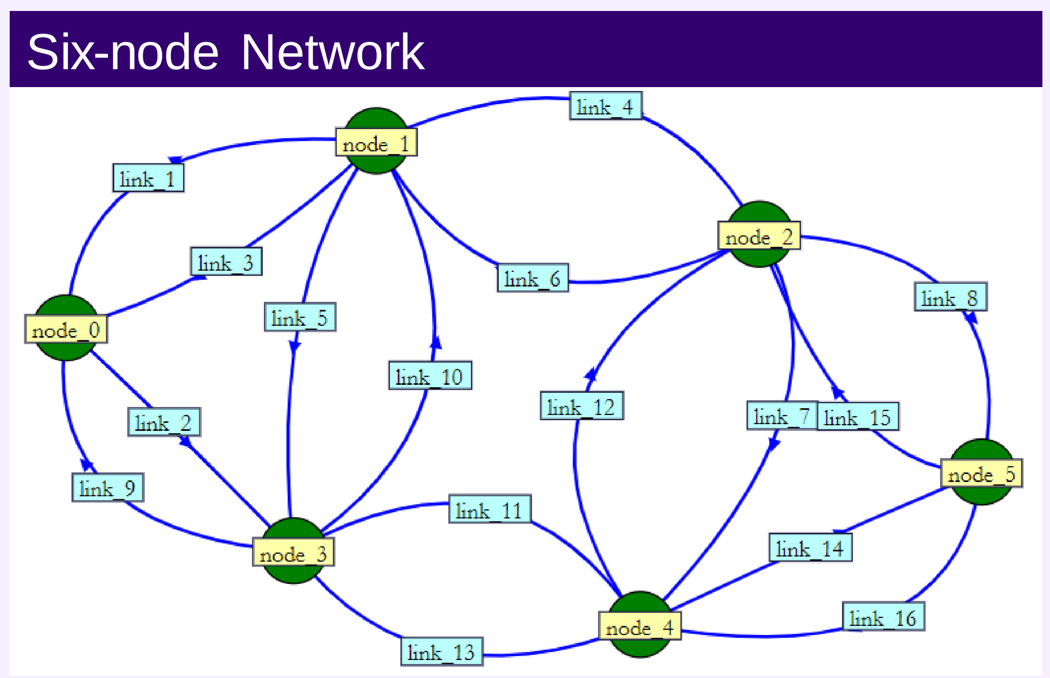
$$Y_{mn,l} \le M_{mn,l} \cdot C_l$$

Other Constraints:

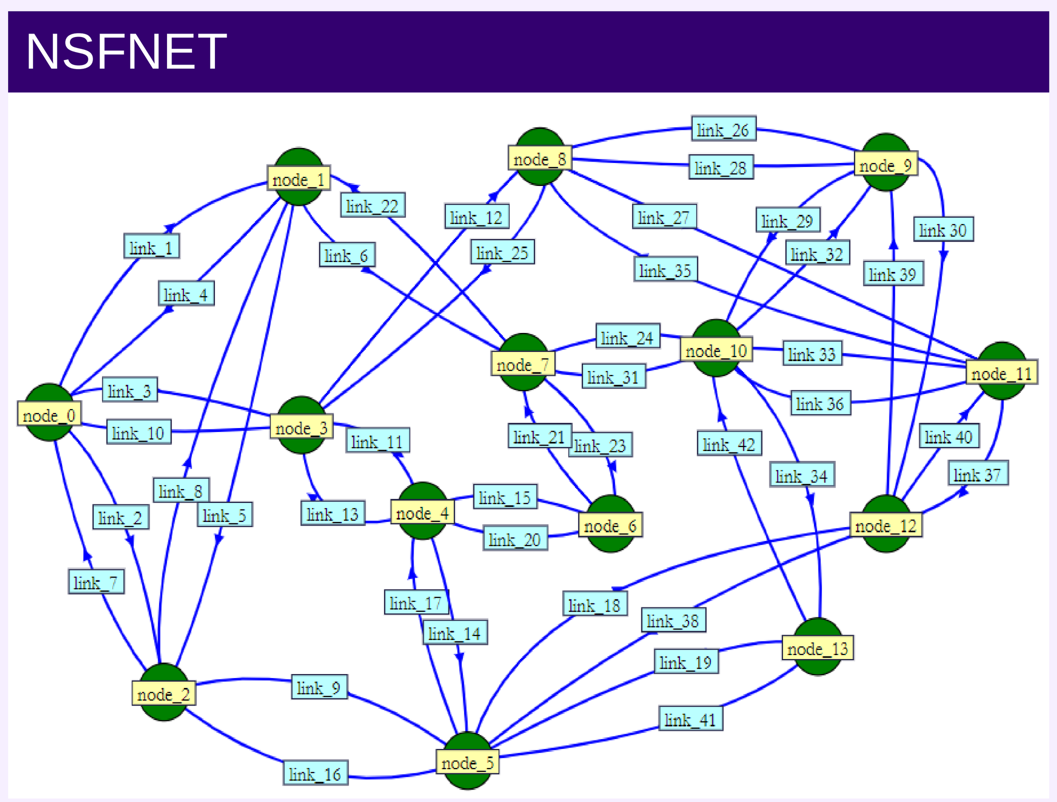
$$Y_{mn,l} \le U \cdot P_{mn,l}$$

- Two testing networks:

Six-node Network



NSFNET



- Two multiplexing techniques:

Deterministic Multiplexing

Resource allocation is based on the **sum** of **maximum** bandwidth required:

$$B = \sum_{i=1}^{n} \mu_i + 3\sum_{i=1}^{n} \sigma_i$$

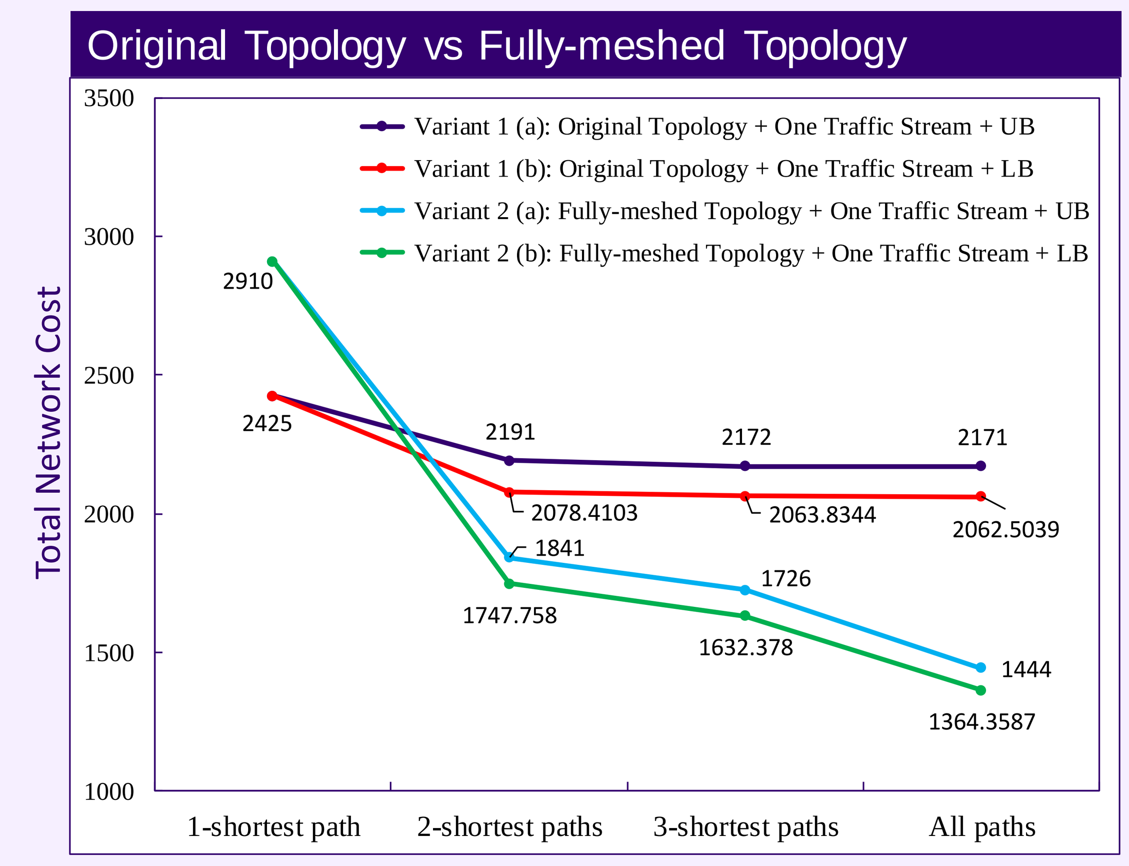
Statistical Multiplexing

Resource allocation is **lower** than the sum of maximum bandwidth required:

$$B = \sum_{i=1}^{n} \mu_i + 3\sqrt{\sum_{i=1}^{n} \sigma_i^2}$$

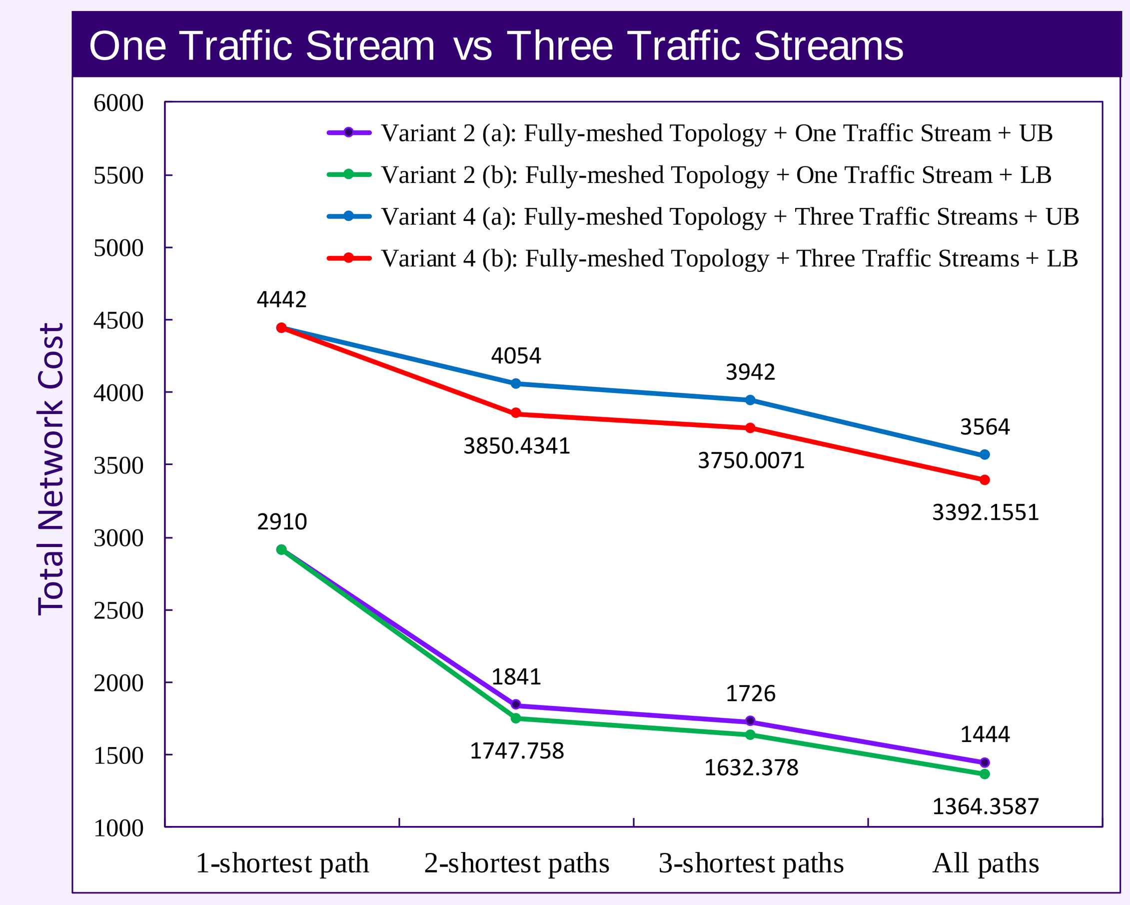
Results

Original Topology vs Fully-meshed Topology

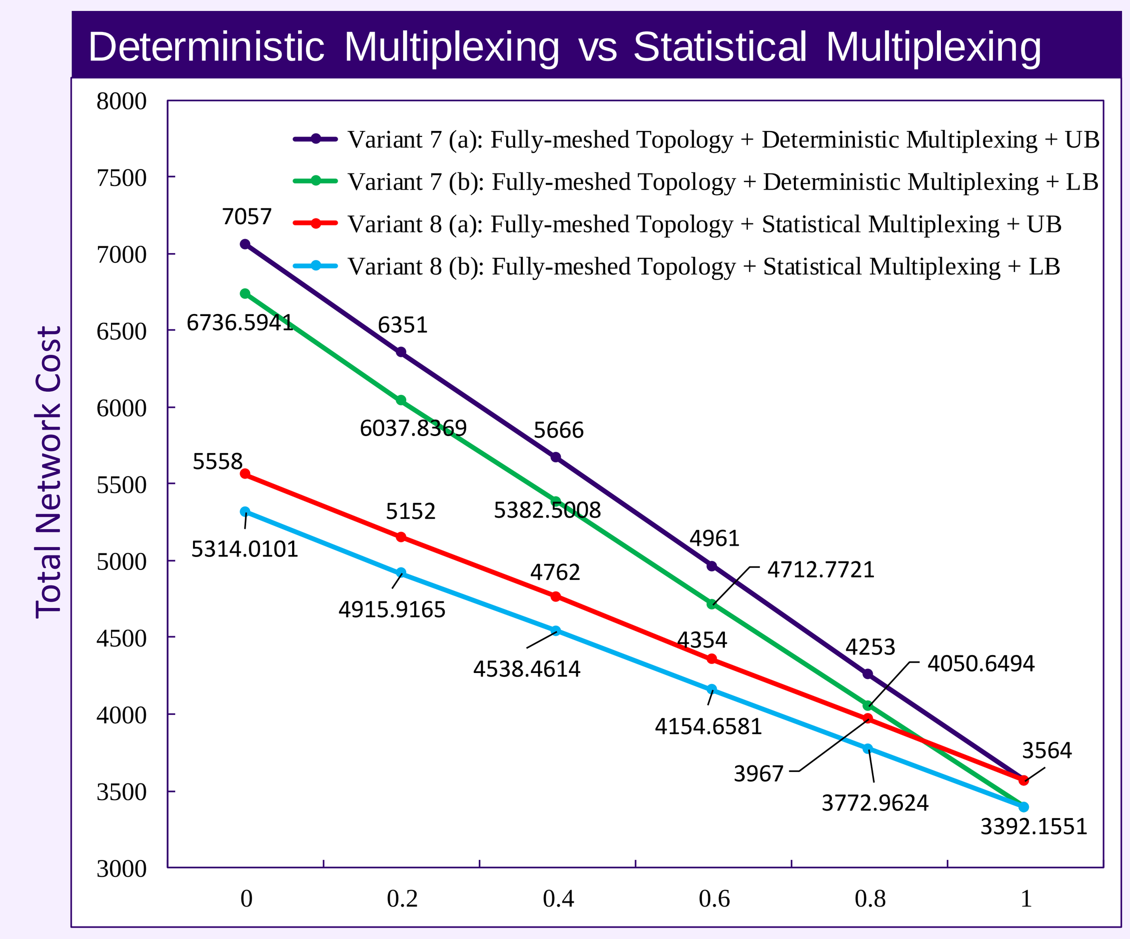


	1-shortest path	2-shortest paths	3-shortest paths	All paths
Original	0.158 secs	3.099 secs	6.855 secs	18.77 secs
Fully-meshed	0.717 secs	12.731 secs	~ 25 hours	~ 72 hours

One Traffic Stream vs Three Traffic Streams



Deterministic Multiplexing vs Statistical Multiplexing



- Number of routing choices ⬆
  Total Network Cost ⬇, Optimization Time ⬆
- Network size ⬆, ILP Efficiency ⬇
- ILP is not scalable, but we can set an appropriate gap tolerance to get tight upper and lower bounds on the optimal solution, serving as benchmarks for other heuristic algorithms.